

**LEVEL**

**12**

DNA 5289F

AD A095122

# METHODS OF FORCE IDENTIFICATION FOR EARTH PENETRATORS

T. Belytschko  
18 Longmeadow Road  
Winnetka, Illinois 60093

1 January 1980

DTIC  
S FEB 18 1981  
C

Final Report for Period 1 July 1976—1 December 1977

CONTRACT No. DNA 001-76-C-0167

APPROVED FOR PUBLIC RELEASE;  
DISTRIBUTION UNLIMITED.

THIS WORK SPONSORED BY THE DEFENSE NUCLEAR AGENCY  
UNDER RDT&E RMSS CODE B344076464 Y99QAXSB04815 H2590D.

Prepared for  
Director  
DEFENSE NUCLEAR AGENCY  
Washington, D. C. 20305

DC FILE COPY

81 2

18 026

Destroy this report when it is no longer needed. Do not return to sender.

PLEASE NOTIFY THE DEFENSE NUCLEAR AGENCY,  
ATTN: STTI, WASHINGTON, D.C. 20305, IF  
YOUR ADDRESS IS INCORRECT, IF YOU WISH TO  
BE DELETED FROM THE DISTRIBUTION LIST, OR  
IF THE ADDRESSEE IS NO LONGER EMPLOYED BY  
YOUR ORGANIZATION.



UNCLASSIFIED

SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

19 REPORT DOCUMENTATION PAGE		READ INSTRUCTIONS BEFORE COMPLETING FORM	
1. REPORT NUMBER 18 DNA 5289F	2. GOVT ACCESSION NO. AD-A095-122	3. RECIPIENT'S CATALOG NUMBER	
4. TITLE (and Subtitle) 6 METHODS OF FORCE IDENTIFICATION FOR EARTH PENETRATORS		5. TYPE OF REPORT & PERIOD COVERED 9 Final Report, 1 Jul 76-1 Dec 77	
7. AUTHOR(s) 10 T. Belytschko		6. PERFORMING ORG. REPORT NUMBER	
9. PERFORMING ORGANIZATION NAME AND ADDRESS T. Belytschko 18 Longmeadow Road Winnetka, Illinois 60093		8. CONTRACT OR GRANT NUMBER(s) 15 DNA 001-76-C-0167	
11. CONTROLLING OFFICE NAME AND ADDRESS Director Defense Nuclear Agency Washington, D.C. 20305		10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS Subtask Y99QAXSB048-15	
14. MONITORING AGENCY NAME & ADDRESS (if different from Controlling Office) 17 B048		12. REPORT DATE 11 1 January 1980	
		13. NUMBER OF PAGES 56 12 57	
		15. SECURITY CLASS (of this report) UNCLASSIFIED	
		15a. DECLASSIFICATION/DOWNGRADING SCHEDULE	
16. DISTRIBUTION STATEMENT (of this Report) Approved for public release; distribution unlimited.			
17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)			
18. SUPPLEMENTARY NOTES This work sponsored by the Defense Nuclear Agency under RDT&E RMSS Code B344076464 Y99QAXSB04815 H2590D.			
19. KEY WORDS (Continue on reverse side if necessary and identify by block number) Penetrators Dynamics Inverse Problem Identification Problem			
20. ABSTRACT (Continue on reverse side if necessary and identify by block number) A procedure is developed for identifying the forces on the nose of a penetrator vehicle from strain time histories at selected points in the vehicle in off-normal impact of the vehicle. The vehicle nose is idealized as a rigid body, the remainder as a deformable rod. The following forces are considered: axial forces, transverse forces in two planes, and bending moments. The deformation response of the vehicle is assumed to be linear. The identification is separated into the identification of the flexural forces and axial forces.			

DD FORM 1473

EDITION OF 1 NOV 65 IS OBSOLETE

UNCLASSIFIED

SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

392212

UNCLASSIFIED

SECURITY CLASSIFICATION OF THIS PAGE(When Data Entered)

20. ABSTRACT (Continued)

Any coupling arising from body forces due to rigid body motion must be neglected. The methods were tested by using analytic and finite element methods to generate strain records and comparing the identified and applied load. Finally, the method was used to identify the loads on a reverse ballistics experiment; the identified loads were evaluated by applying them to a finite element model of the penetrator and comparing the response of this model to the experimental results.

Accession For	
NTIS GRA&I	<input checked="checked" type="checkbox"/>
DTIC TAB	<input type="checkbox"/>
Unannounced	<input type="checkbox"/>
Justification	
By	
Distribution/	
Availability Codes	
Avail and/or	
Dist	Partial
A	

UNCLASSIFIED

SECURITY CLASSIFICATION OF THIS PAGE(When Data Entered)

## TABLE OF CONTENTS

<u>SECTION</u>	<u>Page</u>
I INTRODUCTION	5
II THE FORCE IDENTIFICATION PROBLEM	7
III AXIAL FORCE IDENTIFICATION	16
IV FLEXURAL FORCE IDENTIFICATION	20
V ILLUSTRATIVE RESULTS	25
VI LOADS FOR DNA REVERSE BALLISTIC EXPERIMENTS	34
REFERENCES	50

# LIST OF ILLUSTRATIONS

	<u>PAGE</u>
Figure 1. Depiction of general force identification problem for a penetrator.	8
Figure 2. Coordinate systems and nomenclature.	10
Figure 3. Configuration of sample problem.	26
Figure 4. Applied axial force, $f(t)$ .	27
Figure 5. Axial strain at $x = 7.0$ .	28
Figure 6. Axial strain at $x = 15.0$ .	29
Figure 7. Comparison of actual and identified $f(t)$ using strain at $x = 7.0$ from analytic solution.	30
Figure 8. Comparison of actual and identified $f(t)$ using strain at $x=7.0$ from finite element solution.	32
Figure 9. Comparison of actual and identified moment using strain from finite element solution.	33
Figure 10. DNA-SANDIA vehicle employed in reverse ballistic test.	36
Figure 11. Idealization of SANDIA vehicle for identification problem and finite element model for calculation of response from identified force.	37
Figure 12. Forces identified on nose.	38
Figure 13. Axial acceleration (x-component) at station 7.45 (Accelerometer 2).	39
Figure 14. Axial acceleration (x-component) at station 16.35 (Accelerometer 4)	40
Figure 15. Lateral acceleration (y-component) at station 7.45 (Accelerometer 1)	41
Figure 16. Lateral acceleration (y-component) at station 16.35 (Accelerometer 3)	42
Figure 17. Strain (outside top) at station 9.6 (Strain gauge 3)	43
Figure 18. Strain (outside bottom) at station 9.6 (Strain gauge 10)	44
Figure 19. Strain (inside top) at station 9.6 (Strain gauge 4)	45
Figure 20. Strain (outside top) at station 12.6 (Strain gauge 11)	46

LIST OF ILLUSTRATIONS (cont.)

	<u>Page</u>
Figure 21. Strain (inside bottom) at station 12.6 (Strain gauge 12)	47
Figure 22. Strain (outside top) at station 16 (Strain gauge 13)	48
Figure 23. Strain (inside bottom) at station 16 (Strain gauge 15)	49

## SECTION I

### INTRODUCTION

This report is concerned with the following inverse problem: given the strain response of a penetrator vehicle as functions of time, identify the loads as functions of time. The objective of this effort is to use experimental records of strains in vehicles to determine the forces sustained by a vehicle during penetration. In this effort, attention is limited to the development of appropriate techniques for the problem and the testing of certain aspects of these techniques by comparison with solutions and experimental results.

The identification problem for off-normal impact is quite complex, for it involves separate flexural and axial effects that arise from loads distributed over a fairly large area. In the present investigation, attention is restricted to the linear response of the vehicle, that is, the strains are assumed to remain small and the response is assumed to be elastic. The vehicle is modeled as a uniform rod with the nose represented by a rigid body. Contact stresses are represented as point loads and moments at the center of mass of this rigid body.

The identification problem is subdivided into two parts: the determination of the axial force and the determination of the flexural forces. A simple procedure is developed so that if the axial strain is known as a function of time at any point along the neutral axis of the vehicle, the axial force on the nose can be determined. The determination of the flexural forces requires that strains be measured at a minimum of two stations along the length of the vehicle; at each station, strains must be measured at three points. The procedures are outlined in Sections 2 through 4. In Section 5 some sample results are given which illustrate the effectiveness of the methods for the axial and flexural problem. The methods are then used to identify the forces for a reverse



ballistics experiment (ref. 1). The results are evaluated by applying these identified loads on a detailed finite element model and comparing computed strains and accelerations to experimental records.

## SECTION II

### THE FORCE IDENTIFICATION PROBLEM

In its most general terms, the identification problem consists of determining the distribution of normal and tangential loads on the vehicle as a function of time. This identification must be accomplished from strain gauge records at selected points in the vehicle and perhaps one or two accelerometer records. The elements of this problem are illustrated in Fig. 1.

When considered in this degree of generality, the identification problem is horrendously difficult. The reason for this is explained in the following. Consider the pressures at points A and B, shown in Fig. 1, which are called  $p_n^A$  and  $p_n^B$ , respectively. The response of a strain gauge at C due to the pressures  $p_n^A$  and  $p_n^B$  will differ because the signal from B will arrive sooner than that from A. However, subsequent to the arrival of the wave from B, there is no way to distinguish whether the signal arrived from A or B, unless a strain gauge is located between A and B.

It is possible to distinguish the signals if the expected depth of penetration is known as function of time. However, if the load is to be determined after partial penetration of the nose, this information is of little help since subsequent to penetration beyond B, both points A and B can be sources. This, in conjunction with practical limitations on the number of available strain gauge records, renders the general problem of distributed load identification impractical.

For purposes of formulating a practical force identification problem, we will limit the endeavor to net resultant forces on a specified segment of the vehicle. The following assumptions are made:

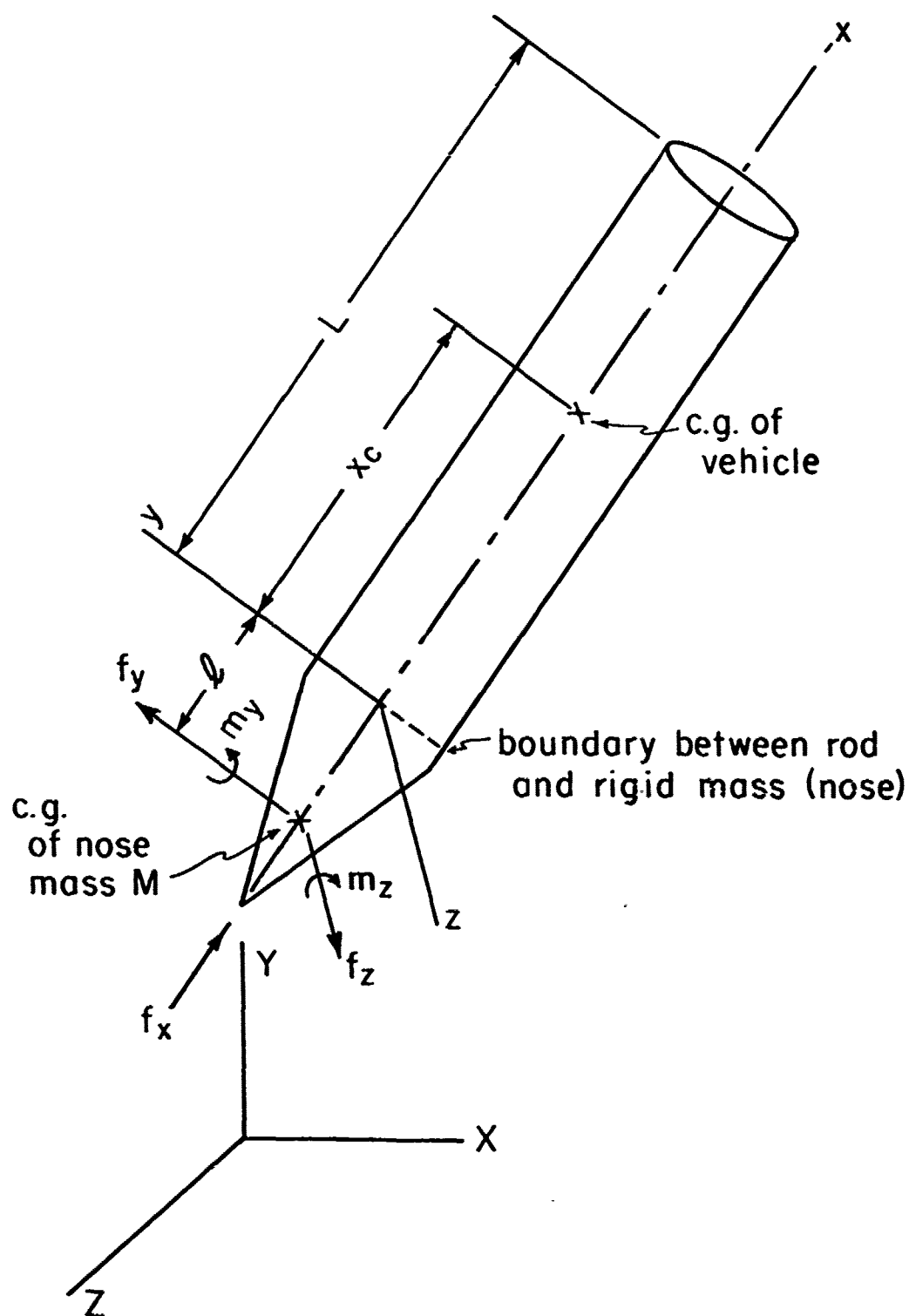


Figure 1. Depiction of general force identification problem for a penetrator.

- i. Contact between the vehicle and medium occurs primarily in the nose region; behind the nose, the medium tends to separate from the vehicle.
- ii. No significant torques about the vehicles axis are exerted, nor does the vehicle spin about its axis.

The first assumption is based largely on normal impact calculations performed by CRT (ref. 2). In off-normal impact, the DNA-SANDIA (ref. 1) experiments have shown significant backslap, so this assumption limits the method to identification of early loads. Without this assumption the identification problem would become very complex. The second assumption is based on the observation that in impact, no mechanism exists which would exert a torque on the vehicle.

The vehicle is modelled as a uniform elastic bar and the nose represented by a rigid body of finite dimensions. This simplification was used in predicting the response to normal impact of the DNA-SANDIA vehicle (ref. 3) and was quite successful. The model is shown in Fig. 1.

The loads to be identified then consist of the following forces and moments on the nose (rigid-body in the model):

- i. the axial force,  $f_x(t)$ , and transverse forces  $f_y(t)$  and  $f_z(t)$
- ii. the moments  $m_y(t)$  and  $m_z(t)$ .

In order to describe the equations governing this model, it is convenient to introduce two coordinate systems:

- i. a moving coordinate system  $(x,y,z)$  embedded in the projectile such that  $x$  always lies along the axis of the vehicle as shown in Fig. 2, with the origin located at the interface between the rigid body and the deformable bar;
- ii. a coordinate system  $(X,Y,Z)$  fixed to the target, which is considered inertial.

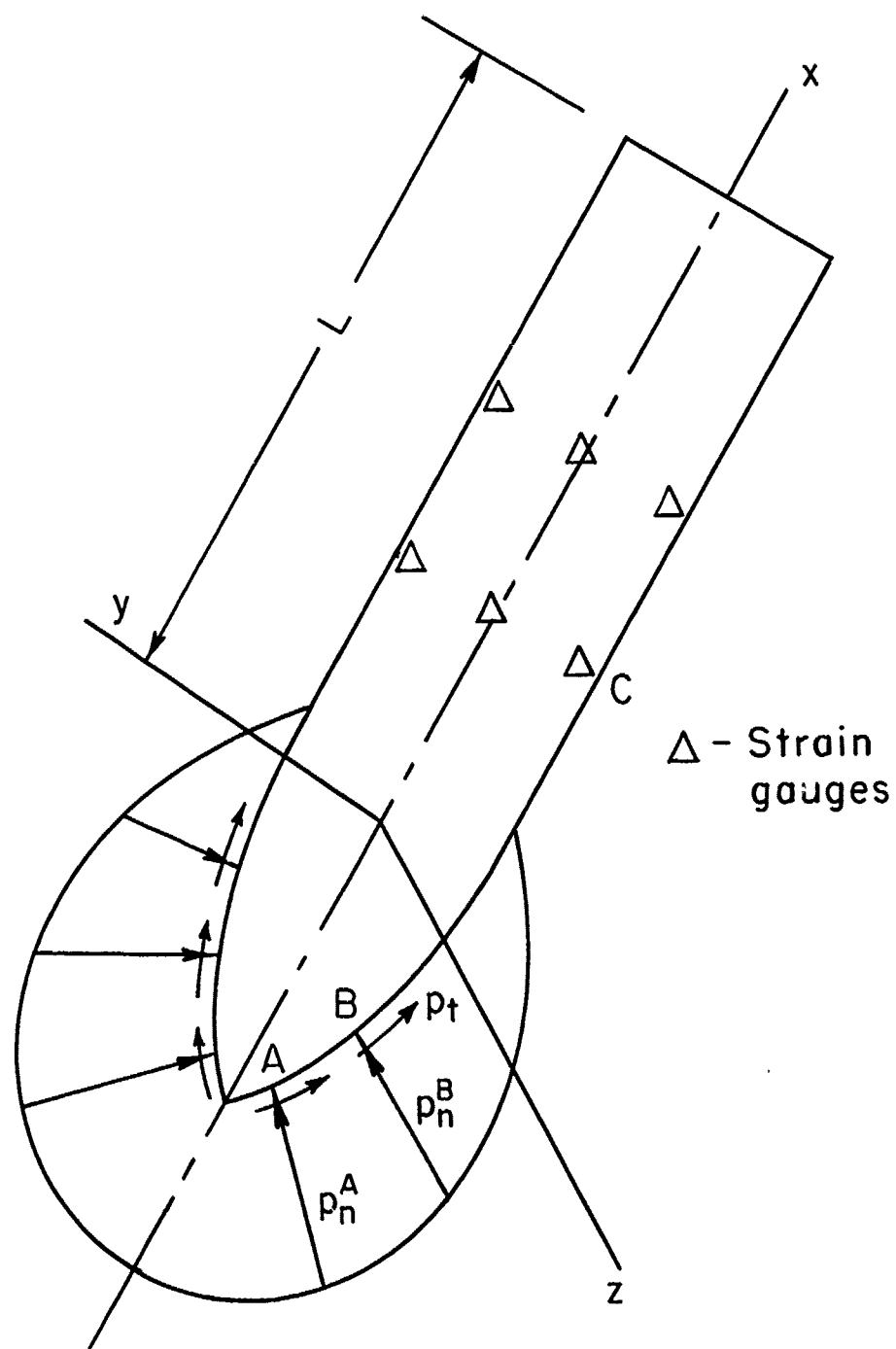


Figure 2. Coordinate systems and nomenclature.

The displacement of a point in the vehicle,  $\vec{r}$ , relative to the vehicle's coordinates is given by a vector  $\vec{v}$  with components  $v_x, v_y, v_z$ , which are assumed to be small. The displacement of the center of mass of the vehicle is denoted by  $\vec{V}$ . The angular velocity and angular acceleration of the vehicle are  $\vec{\omega}$  and  $\vec{\alpha}$ . The acceleration of any point of the vehicle is then

$$\ddot{\vec{R}} = \ddot{\vec{u}} + 2\vec{\omega} \times \dot{\vec{v}} + \vec{\alpha} \times \vec{r} + \vec{\omega} \times (\vec{\omega} \times \vec{r}) \quad (2.1)$$

$$\vec{u} = \vec{V} + \vec{v}$$

Since we assume the vehicle is not spinning, its only nonzero angular velocities are  $\omega_y$  and  $\omega_z$ . Moreover, the vehicle is considered slender and the rotatory inertia of the cross-section will be neglected. From these assumptions it follows that

$$\vec{r} = \bar{x} \vec{i} \quad \bar{x} = x - x_c \quad (2.2)$$

$$\vec{\omega} = \omega_y \vec{j} + \omega_z \vec{k}$$

The acceleration components in the (x,y,z) systems are given by

$$\ddot{R}_x = \ddot{u}_x + 2(\omega_y \dot{v}_z - \omega_z \dot{v}_y) - (\omega_y^2 + \omega_z^2) \bar{x} \quad (2.3)$$

$$\ddot{R}_y = \ddot{u}_y + 2\omega_z \dot{v}_x + \alpha_z \bar{x} \quad (2.4)$$

$$\ddot{R}_z = \ddot{u}_z - 2\omega_y \dot{v}_x - \alpha_y \bar{x} \quad (2.5)$$

Linear strength of materials theory will be employed for describing the dynamic deformation response. Simple first order rod theory which neglects the effects of transverse inertia will be used for the axial response. Euler beam theory will be used for the bending response. The cross-section of the vehicle is assumed to be axisymmetric so that the moment of inertia of the cross-section is isotropic. Therefore bending in the x-y planes and in the y-z planes is uncoupled for any choice of the orientation of the y and z coordinates. Moreover, the axial deformation is uncoupled from bending because of the assumption of small displacements.

The governing equations are then

$$c^2 v_{x,xx} = \ddot{R}_x \quad (2.6)$$

$$c_b^2 v_{y,xxxx} = \ddot{R}_y \quad (2.7)$$

$$c_b^2 v_{z,xxxx} = \ddot{R}_z \quad (2.8)$$

where commas denote derivatives. The accelerations are given by Eqs. (2.3) to (2.5) and

$\rho$  = density of vehicle material

$E$  = Young's modulus of vehicle material

$A$  = cross-sectional area

$I$  = moment of inertia of cross section about both the y and z axes

$c^2 = E/\rho$ , elastic rod wavespeed

$c_b^2 = EI/\rho A$

By using Eqs. (2.3) to (2.5), Eqs. (2.6) to (2.8) can be written as

$$c^2 v_{x,xx} - \ddot{u}_x = b_x \quad (2.9)$$

$$c_b^2 v_{y,xxxx} - \ddot{u}_y = b_y \quad (2.10)$$

$$c_b^2 v_{z,xxxx} - \ddot{u}_z = b_z \quad (2.11)$$

where

$$b_x = 2(\omega_y \dot{v}_z - \omega_z \dot{v}_y) - (\omega_y^2 + \omega_z^2) \bar{x} \quad (2.12)$$

$$b_y = 2\omega_z \dot{v}_x + \alpha_z \bar{x} \quad (2.13)$$

$$b_z = -2\omega_y \dot{v}_x - \alpha_z \bar{x} \quad (2.14)$$

The terms  $b_x$ ,  $b_y$ , and  $b_z$  couple Eqs. (2.9) to (2.11). In order to uncouple the equations we assume that these terms vanish. Since the rigid body motion  $\vec{V}$  is independent of  $x, y$  and  $z$ , its derivatives vanish and we can replace Eqs. (2.9) to (2.11) by

$$c^2 u_{x,xx} - \ddot{u}_x = 0 \quad (2.15)$$

$$c_b^2 u_{y,xxxx} - \ddot{u}_y = 0 \quad (2.16)$$

$$c_b^2 u_{z,xxxx} - \ddot{u}_z = 0 \quad (2.17)$$

The displacements  $u_y$  and  $u_z$  and their second derivatives must be small, but  $u_x$  may be arbitrarily large, although its first derivative must also be small. The boundary conditions are



$$A E u_{x,x} = M\ddot{u} - f_x(t) \quad \text{at } x = 0 \quad (2.18)$$

$$A u_{x,x} = 0 \quad \text{at } x = L$$

$$-E I u_{y,xxx} = M(\ddot{u}_y - l\ddot{u}_{y,x}) - f_y(t) \quad (2.19)$$

$$E I (u_{y,xx} - l u_{y,xxx}) = J \ddot{u}_{y,x} - m_z(t) \quad \text{at } x = 0$$

$$-E I u_{z,xxx} = M(\ddot{u}_z - l\ddot{u}_{z,x}) - f_z(t)$$

$$E I (u_{z,xx} - l u_{z,xxx}) = J \ddot{u}_{z,x} + m_y(t) \quad (2.20)$$

$$u_{z,xx} = u_{z,xxx} = 0 \quad \text{at } x = L$$

where  $J$  is the moment of inertia of the rigid body. Initial conditions provide the initial velocity of the projectile.

The strain at any point  $x, y, z$  in the structure is given by

$$\varepsilon(x, y, z, t) = u_{x,x} - y u_{y,xx} - z u_{z,xx} \quad (2.21)$$

The identification problem then consists of the following: given strain histories at selected points  $x_i, y_i, z_i$ , determine the forces  $f_x(t), f_y(t)$ , and  $f_z(t)$  and the moments  $m_y(t)$  and  $m_z(t)$ . For convenience, we denote by  $\{F(t)\}$  the complete matrix of forces to be determined:  $\{f_x, f_y, f_z, m_y, m_z\}$ .

When strain records at three different points  $y_j, z_j$  are given at any cross section  $x_i$ , then Eq. (2.21) can be solved uniquely to yield the response  $\{r(t)\} = \{u_{x,x}(x_i, t), u_{y,xx}(x_i, t), u_{z,xx}(x_i, t)\}$  provided that the matrix

$$[A] = \begin{bmatrix} 1 & -y_1 & -z_1 \\ 1 & -y_2 & -z_2 \\ 1 & -y_3 & -z_3 \end{bmatrix} \quad (2.23)$$

is not singular

The matrix  $[A]$  is singular if and only if all three points are collinear. Thus any triangular arrangement of the points  $y_j, z_j$  is sufficient to permit the determination of  $\{r(t)\}$ .

Once  $\{r(t)\}$  is given. The complete identification problem can be subdivided into three uncoupled parts:

- i. given  $\varepsilon = u_{x,x}(x_i, t)$ , determine  $f_x$  through Eq. (2.15) and boundary conditions (2.18)
- ii. given  $u_{y,xx}(x_i, t)$ , determine  $m_z$  and  $f_y$  through Eq. (2.16) and boundary conditions (2.19)
- iii. given  $u_{z,xx}(x_i, t)$ , determine  $m_y$  and  $f_z$  through Eq. (2.17) and boundary conditions (2.20).

Problem (i) is an axial problem, problems (ii) and (iii) identical flexural problems; they are discussed in Sections 3 and 4, respectively. For two dimensional problems, where the motion of the vehicle is planar, only problems (i) and (ii) need be solved.

### SECTION III

#### AXIAL FORCE IDENTIFICATION

We consider here the problem of the identification of the axial load. The axial response problem is governed by the equations and boundary conditions (subscripts  $x$  are omitted in this section)

$$u_{,xx} = \frac{1}{c^2} \ddot{u} \quad (3.1)$$

$$AE u_{,x} = M \ddot{u} - f(t) \quad \text{at } x = 0 \quad (3.2)$$

$$u_{,x} = 0 \quad \text{at } x = L \quad (3.3)$$

which correspond to Eqs. (2.9) and (2.18). The initial conditions are taken to be

$$u(x,0) = 0 \quad (3.4)$$

$$\dot{u}(x,0) = 0 \quad (3.5)$$

The problem is to obtain the time history of the net force on the nose,  $f(t)$ , given the axial strain time history at one point.

We will use Laplace transform techniques. Let the Laplace transform of a given variable be denoted by a corresponding upper case letter, i.e.  $U(x,s)$  is the Laplace transform  $u(x,t)$ , so that

$$U(x,s) = \int_0^{\infty} u(x,t) e^{-st} dt \quad (3.6)$$

Similarly  $E(s)$  is the Laplace transform of  $\varepsilon(t)$ ,  $F(s)$  the Laplace transform of  $f(t)$ .

Taking the Laplace transform of Eq. (3.1) and noting that the initial conditions are zero, get

$$U_{,xx}(x,s) = \frac{s^2}{c^2} U(x,s) \quad (3.7)$$

which has the solution

$$U(x,s) = K_1 e^{-sx/c} + K_2 e^{sx/c} \quad (3.8)$$

The Laplace transforms of the boundary conditions, (3.2) and (3.3), give

$$AEU_{,x}(0,s) = M s^2 U(0,s) - F(s) \quad (3.9)$$

$$U_{,x}(L,s) = 0 \quad (3.10)$$

Substituting Eq. (3.8) into Eqs. (3.9) and (3.10) yields two linear, algebraic equations in  $K_1$  and  $K_2$ , the solution of which is

$$K_1 = e^{2Ls/c} F(s)/G(s) \quad (3.11)$$

$$K_2 = F(s)/G(s) \quad (3.12)$$

where

$$G(s) = s \left[ \left( Ms + \frac{AE}{c} \right) e^{2Ls/c} + \left( Ms - \frac{AE}{c} \right) \right] \quad (3.13)$$

From Eq. (3.8), it also follows that the Laplace transform of the strain at any point  $x_i$  is given by

$$\mathcal{E}(x_i, s) = \frac{s}{c} [-K_1 e^{-sx_i/c} + K_2 e^{sx_i/c}] \quad (3.14)$$

Substituting Eqs. (3.11) and (3.12) into (3.14) and solving for  $F(s)$  yields

$$F(s) = \frac{1}{sH(s)} c \mathcal{E}(x_i, s) G(s) \quad (3.15a)$$

$$H(s) = e^{x_i s/c} - e^{(2L-x_i)s/c} \quad (3.15b)$$

Substituting Eq. (3.13) into Eq. (3.15), we can write the latter as

$$F(s) = \frac{\mathcal{E}(x_i, s)}{H(s)} [(Mcs + AE)e^{2Ls/c} + (Mcs - AE)] \quad (3.16)$$

The time domain counterpart of Eq. (3.16) is

$$\begin{aligned} f(t + \frac{x_i}{c}) - f(t + \frac{2L-x_i}{c}) &= Mc\dot{\mathcal{E}}(x_i, t) - AE\mathcal{E}(x_i, t) \\ &+ Mc\dot{\mathcal{E}}(x_i, t + \frac{2L}{c}) + AE\mathcal{E}(x_i, t + \frac{2L}{c}) \end{aligned} \quad (3.17)$$

Thus by shifting in time by  $(2L-x_i)/c$ , we obtain from Eq. (3.17) that

$$\begin{aligned} f(t) &= f(t - 2(L-x_i)/c) + AE [\mathcal{E}(x_i, t - \frac{2L-x_i}{c}) - \mathcal{E}(x_i, t + \frac{x_i}{c})] \\ &- Mc [\dot{\mathcal{E}}(x_i, t + \frac{x_i}{c}) - \dot{\mathcal{E}}(x_i, t - \frac{2L-x_i}{c})] \end{aligned} \quad (3.18)$$

From the above equation, it is apparent that once an axial strain record is known at any given point, the force history can be determined. Although a Laplace transform approach has been used, from the time shifts that occur in the equations, it is apparent that this result follows from the nature of the solution to the wave equation. The solution always consists of a wave induced by the force which moves to the left and an image moving to the right, shifted in time by  $L/c$ , which maintains the stress free condition on the right end of the rod. The Laplace transform approach serves to formalize these results.

## SECTION IV

### FLEXURAL FORCE IDENTIFICATION

From each flexural equation, two quantities, a force and a moment, must be determined. The flexural equation and associated boundary conditions, Eqs. (2.10) or (2.11), and (2.19) or (2.20), can be written

$$w_{,xxxx} + \frac{1}{c_b} \ddot{w} = 0 \quad (4.1)$$

$$w_{,xxx} = c_1 (\ddot{w} - \lambda \ddot{w}_{,x}) - f \quad \text{at } x = 0 \quad (4.2)$$

$$w_{,xx} - \lambda w_{,xxx} = c_2 \ddot{w}_{,x} - m \quad \text{at } x = 0 \quad (4.3)$$

$$w_{,xx} = 0 \quad \text{at } x = L \quad (4.4)$$

$$w_{,xxx} = 0 \quad \text{at } x = L \quad (4.5)$$

where

$$c_b^2 = \frac{EI}{\rho A} \quad (4.6)$$

$$c_1 = \frac{M}{EI} \quad (4.7)$$

$$c_2 = \frac{J}{EI} \quad (4.8)$$

The problem is to identify  $f(t)$  and  $m(t)$  from records of the curvature  $w_{,xx}(x_i, t)$ . As in Section 3, we will use a Laplace transform approach and denote the Laplace transform by upper case letters.

Taking the Laplace transform of Eq. (4.1) yields

$$W_{,xxxx} + \frac{s}{2c_b} W = 0 \quad (4.9)$$

for which the solution is

$$W(x,s) = K_1 e^{\gamma_1 x} + K_2 e^{-\gamma_1 x} + K_3 e^{\gamma_2 x} + K_4 e^{-\gamma_2 x} \quad (4.10)$$

$$\gamma_1 = (1 + j) \sqrt{\frac{s}{2c_b}} \quad \gamma_2 = (1 - j) \sqrt{\frac{s}{2c_b}} \quad (4.11)$$

and  $K_i$  are functions of  $s$ , and

$$j = \sqrt{-1} \quad (4.12)$$

The boundary conditions at  $x = 0$  and  $x = L$  can be written in partitioned matrix form in terms of  $W(x,s)$  as follows

$$\begin{bmatrix} [H_{11}] & [H_{12}] \\ [H_{21}] & [H_{22}] \end{bmatrix} \begin{Bmatrix} K_1 \\ K_2 \\ K_3 \\ K_4 \end{Bmatrix} = \begin{Bmatrix} F \\ M \\ 0 \\ 0 \end{Bmatrix} \quad (4.13)$$

$$[H_{11}] = \begin{bmatrix} c_1 s^2 (1 - \gamma_1 \ell) + \gamma_1^3 & c_1 s^2 (1 + \gamma_1 \ell) - \gamma_1^3 \\ \gamma_1^2 (1 - \gamma_1 \ell) - c_2 s^2 \gamma_1 & \gamma_1^2 (1 + \gamma_1 \ell) + c_2 s^2 \gamma_1 \end{bmatrix} \quad (4.14a)$$



$$[H_{12}] = \begin{bmatrix} c_1 s^2 (1 - \gamma_2 \ell) + \gamma_2^3 & c_1 s^2 (1 + \gamma_2 \ell) - \gamma_2^3 \\ \gamma_2^2 (1 - \gamma_2 \ell) - c_2 s^2 \gamma_2 & \gamma_2^3 (1 + \gamma_2 \ell) + c_2 s^2 \gamma_2 \end{bmatrix} \quad (4.14b)$$

$$[H_{21}] = \gamma_1^2 \begin{bmatrix} \gamma_1 \ell e^{\gamma_1 \ell} & -\gamma_1 \ell e^{-\gamma_1 \ell} \\ \gamma_1 e^{\gamma_1 \ell} & -\gamma_1 e^{-\gamma_1 \ell} \end{bmatrix} \quad (4.14c)$$

$$[H_{22}] = \gamma_2^2 \begin{bmatrix} \gamma_2 \ell e^{\gamma_2 \ell} & -\gamma_2 \ell e^{-\gamma_2 \ell} \\ \gamma_2 e^{\gamma_2 \ell} & -\gamma_2 e^{-\gamma_2 \ell} \end{bmatrix} \quad (4.14d)$$

The transform of the response, at any point  $x_i$ , is given by

$$W_{xx}(x_i, s) = K_1 \gamma_1^2 e^{\gamma_1 x_i} + K_2 \gamma_1^2 e^{-\gamma_1 x_i} + K_3 \gamma_2^2 e^{\gamma_2 x_i} + K_4 \gamma_2^2 e^{-\gamma_2 x_i} \quad (4.15)$$

If the curvature is given at two points,  $x_1$  and  $x_2$ , then we can write

$$\begin{Bmatrix} W(x_1, s) \\ W(x_2, s) \end{Bmatrix} = \begin{bmatrix} [L_{11}] & [L_{12}] \end{bmatrix} \begin{Bmatrix} K_1 \\ K_2 \\ K_3 \\ K_4 \end{Bmatrix} \quad (4.16)$$

From Eq. (4.13), it follows that

$$\begin{Bmatrix} K_3 \\ K_4 \end{Bmatrix} = -[H_{22}]^{-1} [H_{21}] \begin{Bmatrix} K_1 \\ K_2 \end{Bmatrix} \quad (4.17)$$

Hence

$$\begin{Bmatrix} W(x_1, s) \\ W(x_2, s) \end{Bmatrix} = \begin{bmatrix} [L_{11}] & [L_{12}] [H_{22}]^{-1} [H_{21}] \end{bmatrix} \begin{Bmatrix} K_1 \\ K_2 \end{Bmatrix} \quad (4.18)$$

If we call the above square matrix  $[G]$ , Eqs. (4.14) and (4.18) yield

$$\begin{Bmatrix} F(s) \\ M(s) \end{Bmatrix} = \begin{bmatrix} [H_{11}] & [H_{12}] [H_{22}]^{-1} [H_{21}] \end{bmatrix} [G]^{-1} \begin{Bmatrix} W(x_1, s) \\ W(x_2, s) \end{Bmatrix} \quad (4.19)$$

An explicit transformation of the above into the time domain is impossible. Instead, the operations of Eq. (4.19) were carried out in the frequency domain, using Fast Fourier Transform algorithms.

The procedure consists of the following. Transforms are obtained of the response  $w_{xx}$  at two points. The transfer function relating the input to the response is then evaluated; its product with the response yields the transform of the forcing function. The inverse transform of the forcing functions are then taken to obtain the forcing functions in the time domain.

The submatrix  $[H_{22}]$  is singular at  $s = 0$  (rigid body mode) and at the natural frequencies. To make the inversion possible, artificial damping is added to the system. This displaces the zeroes from the imaginary axis and so avoids the singularities.

Note that the number of distinct forces that can be identified depends on the number of response records. Two response records are needed to identify the force and moment on the nose. If backslap is to be identified, it could be represented by an inhomogeneous term in the boundary condition Eq. (4.5); responses at three points along the axis of the vehicle would then be needed.

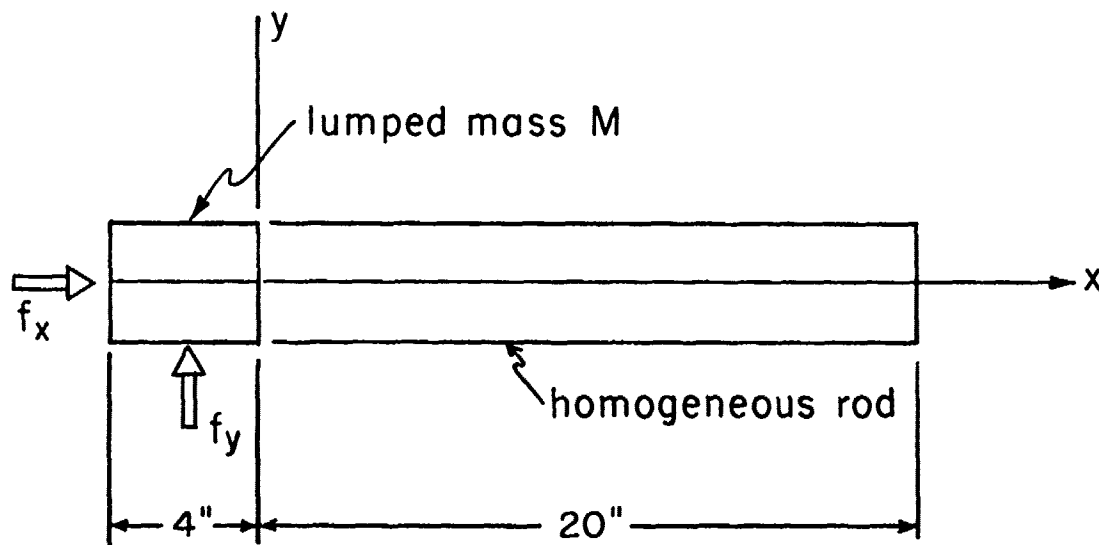
## SECTION V

### ILLUSTRATIVE RESULTS

The force identification procedures for the axial force and the flexural forces have been tested through the use of analytic and finite element solutions. Analytic solutions were used to test the procedure as follows: the strain was predicted for a prescribed forcing function at the nose, and this strain was then used as input to the identification procedure. The identified load was then compared with the actual force. The finite element test was similar except that finite element solutions were used rather than an analytical solution to obtain the strains from the forces.

In both tests, the vehicle described in Fig. 3 was used. The first test involved only an axial load with the time history shown in Fig. 4. The responses at  $x = 7\text{in.}$  and  $15\text{in.}$  are shown in Figs. 5 and 6. Figure 7 shows the force as computed from the identification procedure given in Section 3, and compares the results to the applied load. As can be seen, the identified axial load corresponds closely with the actual load. There are some discrepancies at the points at which the slope of the actual load is discontinuous; the identified load at those points tends to smooth over these discontinuities.

The same procedure was repeated with the finite element solution. The finite element solution shows the effect of the vehicle idealization and the sensitivity of the identification procedure to spurious oscillations. Finite element solutions have spectral amplification and cut-offs similar to strain gauges. The identified force is compared to the actual force in Fig. 8. As can be seen, for the finite element solution, the identified force does not correspond as closely to the actual input force as in the case of the analytic



$$Mg = 12.0 \text{ lbs.}$$

$$A = 4.41 \text{ in}^2$$

$$E = 2.85 \times 10^7 \text{ psi}$$

$$\rho = 0.000732 \text{ lb.} \cdot \text{sec}^2/\text{in}^4$$

Figure 3. Configuration of sample problem.

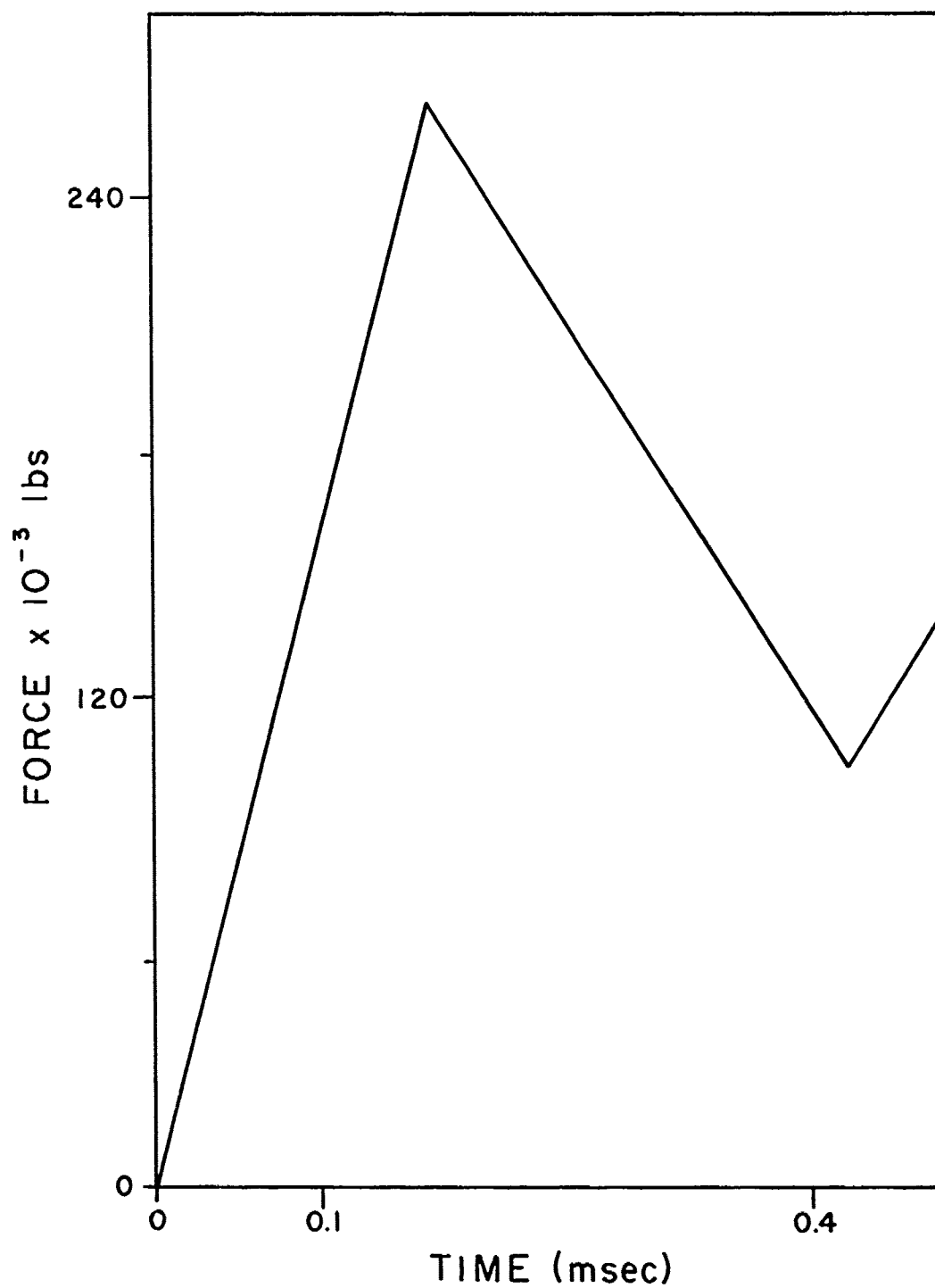


Figure 4. Applied axial force,  $f(t)$

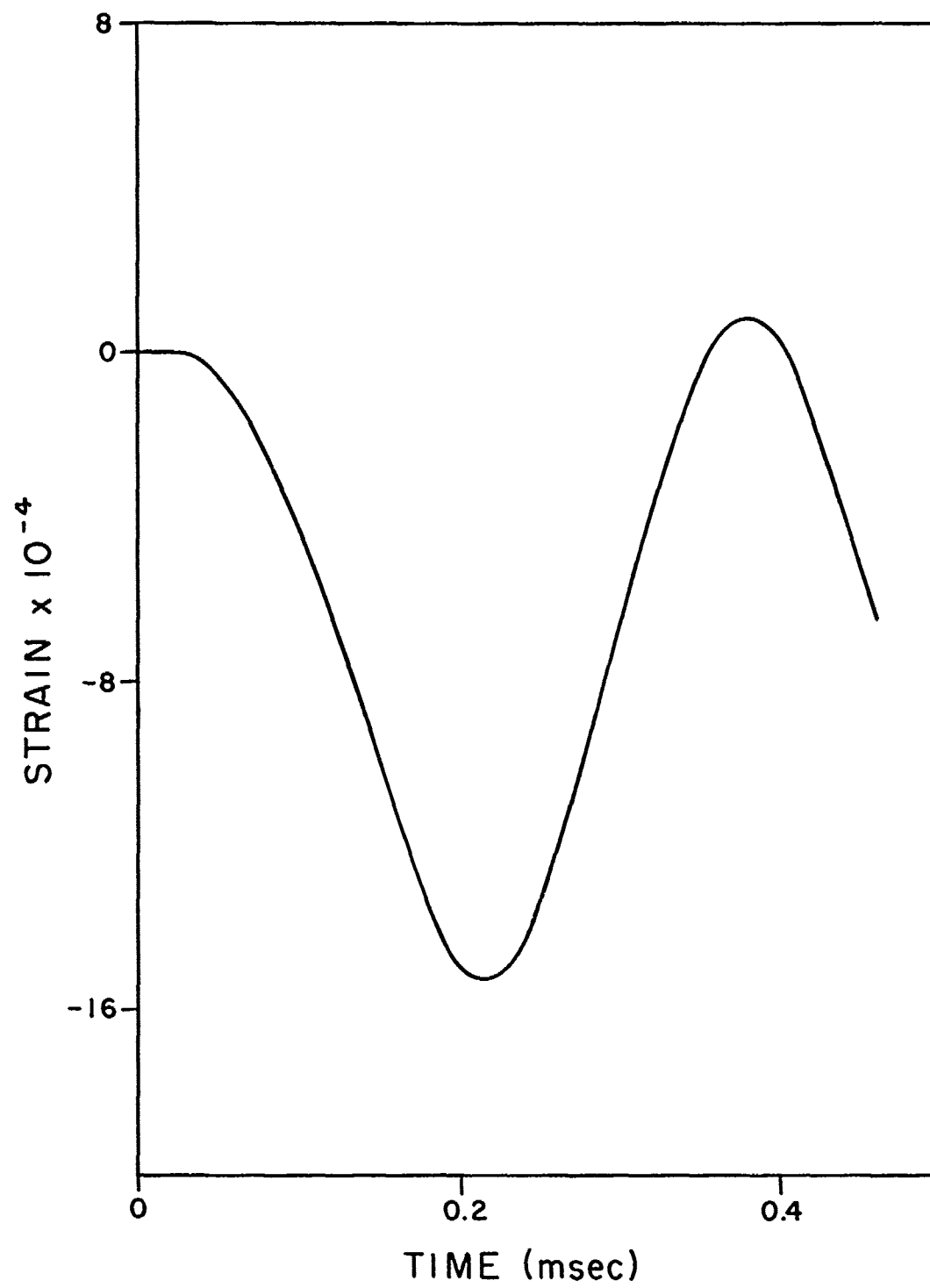


Figure 5. Axial strain at  $x = 7.0$ .

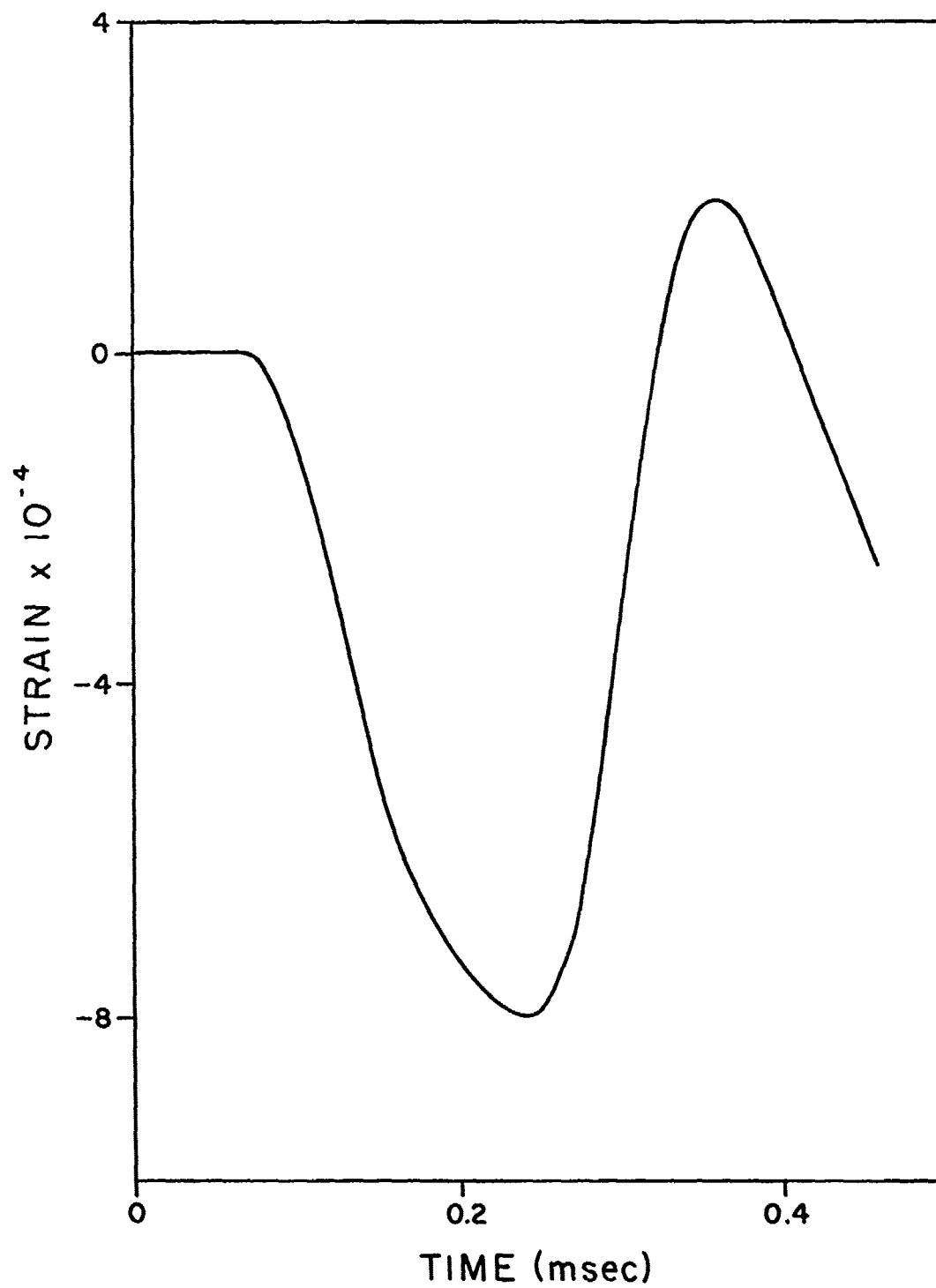


Figure 6. Axial strain at  $x = 15.0$ .



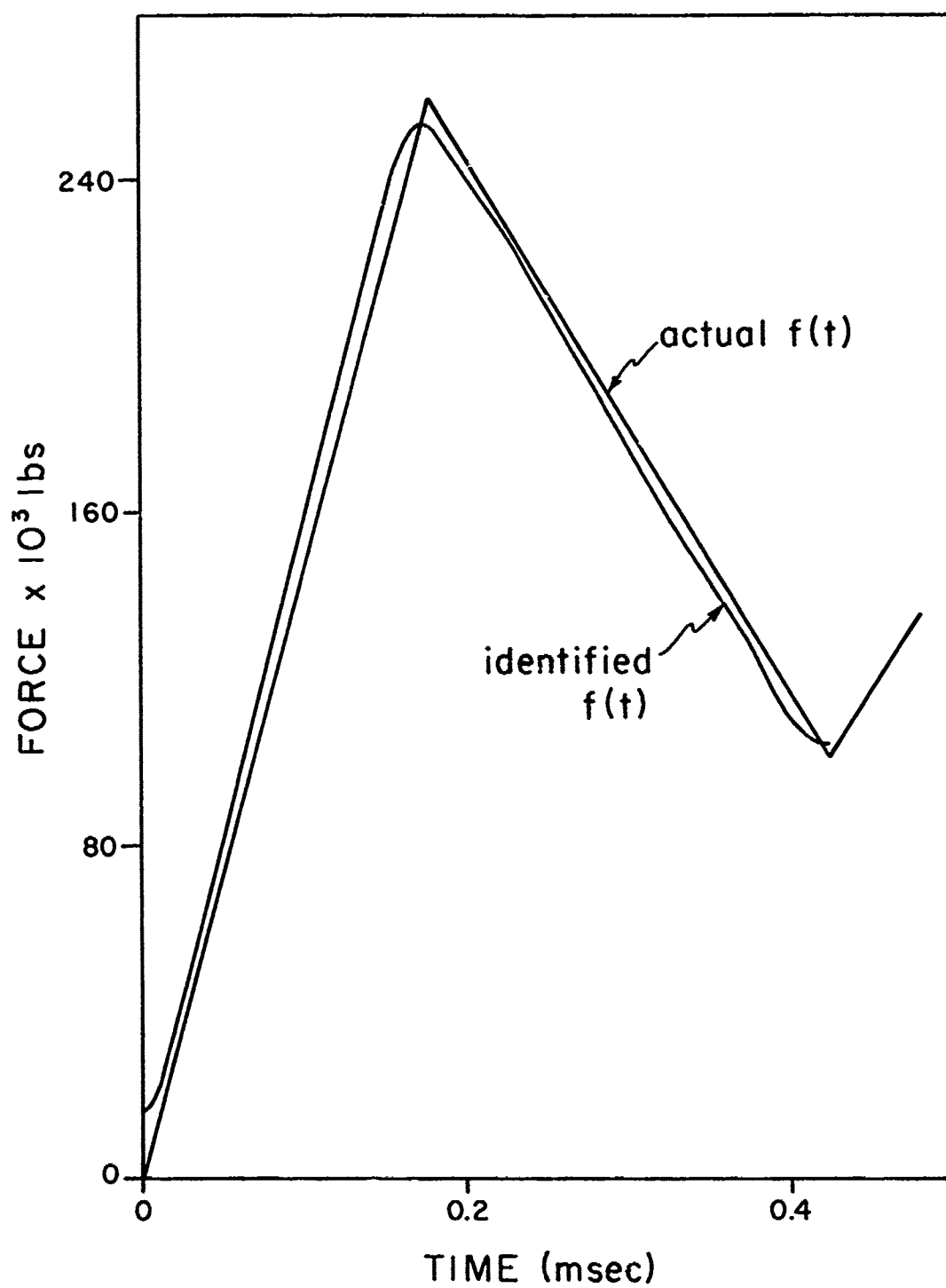


Figure 7. Comparison of actual and identified  $f(t)$  using strain at  $x = 7.0$  from analytic solution.

solution. There is a more pronounced oscillation about the actual solution. Some of these oscillations may be removable by digital filtering.

In the third example, a moment with a time history was applied to the nose in addition to an axial force on a finite element model. The identified loads are compared to the applied loads in Fig. 9. In this case, the identification is not as accurate as for the axial force. The use of numerical transforms introduces substantial errors unless tremendous resolution is used in the frequency domain. The identification shown here represents a compromise between adequate resolution and reasonable computer time. The maximum moment and salient aspects of the time history are well represented; but the predicted moment exhibits a significant lag.

Numerical experiments have also been carried out in identifying both the moment and shear from curvature records at two stations. These have been quite unsatisfactory. To obtain a transfer function which is invertible, considerable damping is needed, and the identified forces and moments are quite sensitive to the magnitude of the damping. Therefore, in the following section, only the transverse force was identified for the flexural problem.

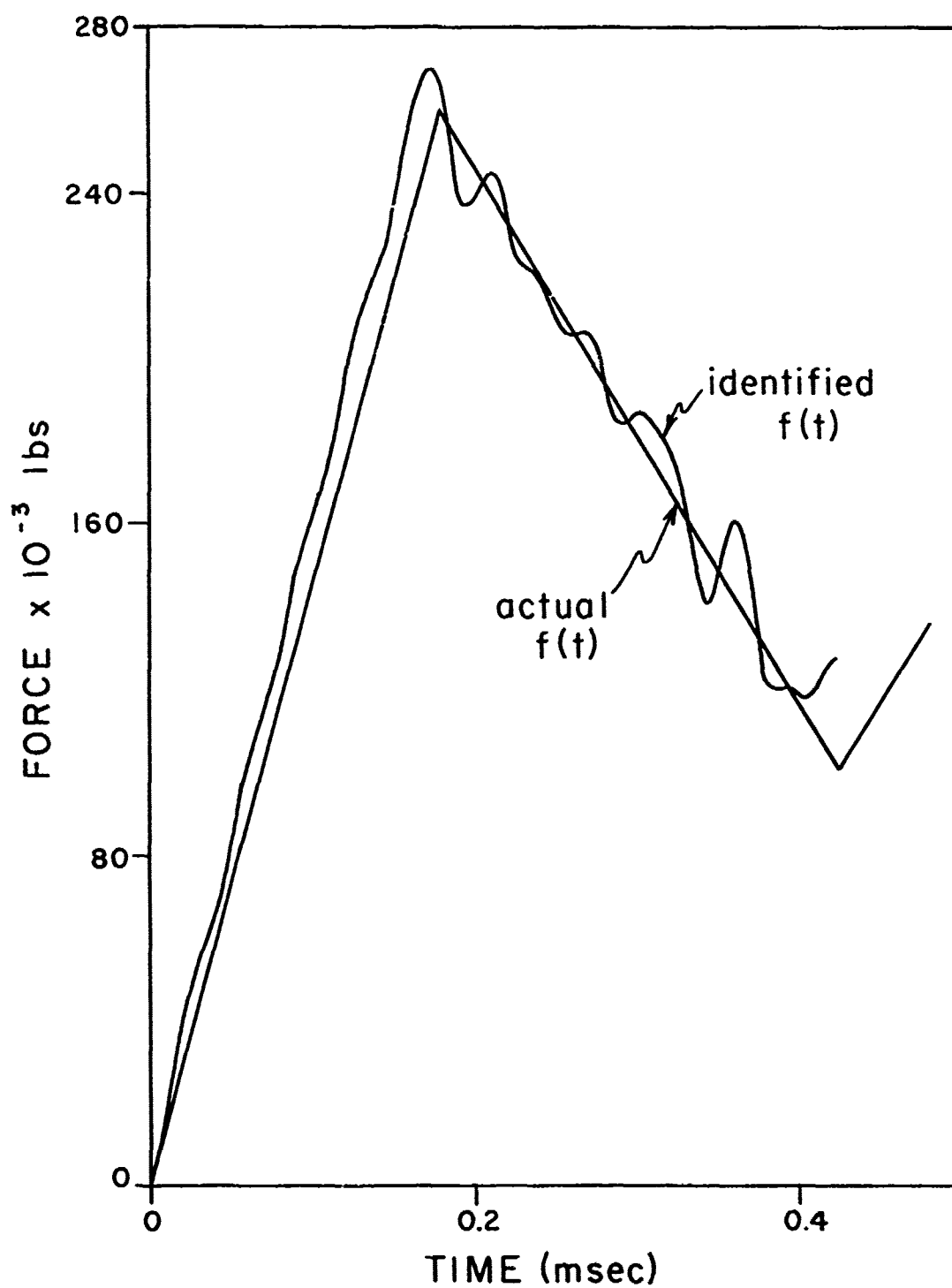


Figure 8. Comparison of actual and identified  $f(t)$  using strain at  $x = 7.0$  from finite element solution.

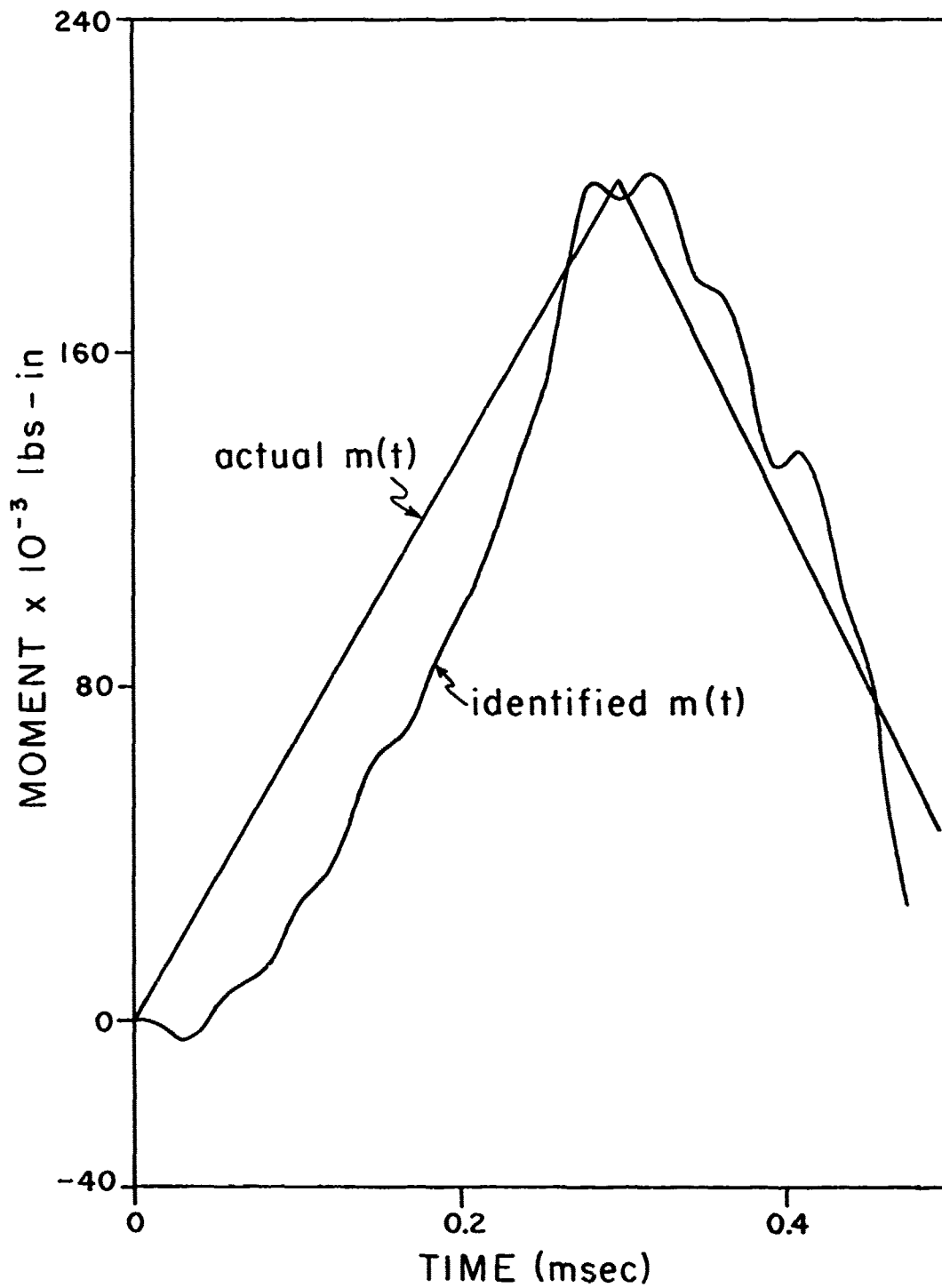


Figure 9. Comparison of actual and identified moment using strain from finite element solution.

SECTION VI  
LOADS FOR DNA REVERSE BALLISTIC  
EXPERIMENTS

We will here describe the loads identified for the DNA reverse ballistic experiments conducted at Sandia Laboratories (ref. 1). The study is limited to Test 3 in which the projectile was in a 3 degree nose-down attitude; i.e. the angle of attack was 3 degrees. Test data consisted of four accelerometer records, two axial and two lateral, and seventeen axial strain gauges.

In this Section, we will describe the simplifications which were necessary to generate a model suitable for the force identification. Once the forces were identified, they were applied to a detailed finite element model of the projectile. The strains and accelerations predicted by the finite element model are then compared to experimental results.

A schematic of the projectile is shown in Fig. 10. The idealization employed for the force identification is shown in Fig. 11. Several features of the projectile had to be omitted because the identification model is limited to a single rigid mass and a rod of uniform properties. The rigid mass was used to model the portion of the projectile between 0 and 3.45 inches. The uniform rod was then given the dimensions of an average cross-section. In the actual model, we have four distinct sections behind the nose (1) the kennertium plug and steel barrel from 3.45 inches to 7.45 inches; (2) the 1.702 inch O.D. section from 7.45 inches to 9.64 that houses the front accelerometers; (3) the tapered section from 9.64 inches to 13.04 inches, in which the O.D. increases from 1.702 inches to 1.900 inches; (4) the last constant diameter section from 13.045 inches to 18.15 inches. The idealized model is too stiff in comparison to the first half of the vehicle, and too

flexible in comparison to the second half.

The loads were identified from the strain gauge records at station 9.6 inches, gauges 3 and 10. (shown in Figs. 17 and 18). This location was chosen because it is as far as possible from the irregularities near the front accelerometer and relatively clean records were obtained in Test 3. The force was identified only for 0.4 msec; after that time the vehicle penetrates beyond the nose.

The identified axial and transverse loads are shown in Fig. 12. The maximum axial load is 130,000 lbs. and occurs at 300 microseconds; the maximum transverse load is 26,000 lbs. and occurs at 50 microseconds. Both of the records shown were extensively filtered.

These loads were then applied to the finite element model shown in Fig. 11 for a 0.6 msec simulation, the loads at 0.4 msec were held constant. The model was solved by the program WHAMS - 2D (ref. 4) using explicit time integration. All acceleration results were smoothed by a 10 point averaging filter (ref. 5). The acceleration results are compared to the four accelerometer records for Test 3 in Figs. 13 to 16. As can be seen, the axial accelerations, Figs. 13 and 14, agree quite well with the experiment, indicating that the axial load identification was successful. The agreement of the lateral records, Figs. 15 and 16, is quite poor.

Strain gauge output is compared to the experiment in Figs. 17 to 23. Particularly for the first 0.4 msec, the agreement is satisfactory. The increasing discrepancy after this time is understandable since the loads were only identified to 0.4 msec. However, it is unclear why the agreement in lateral accelerations is so poor in comparison to the strains. A possible explanation may lie in the nonuniqueness of the identification problem. If a different model were selected, the nonuniqueness may lead to substantially different lateral forces but still the same strains. It is this nonuniqueness which is also undoubtedly related to the numerical difficulties of inverting the problem.

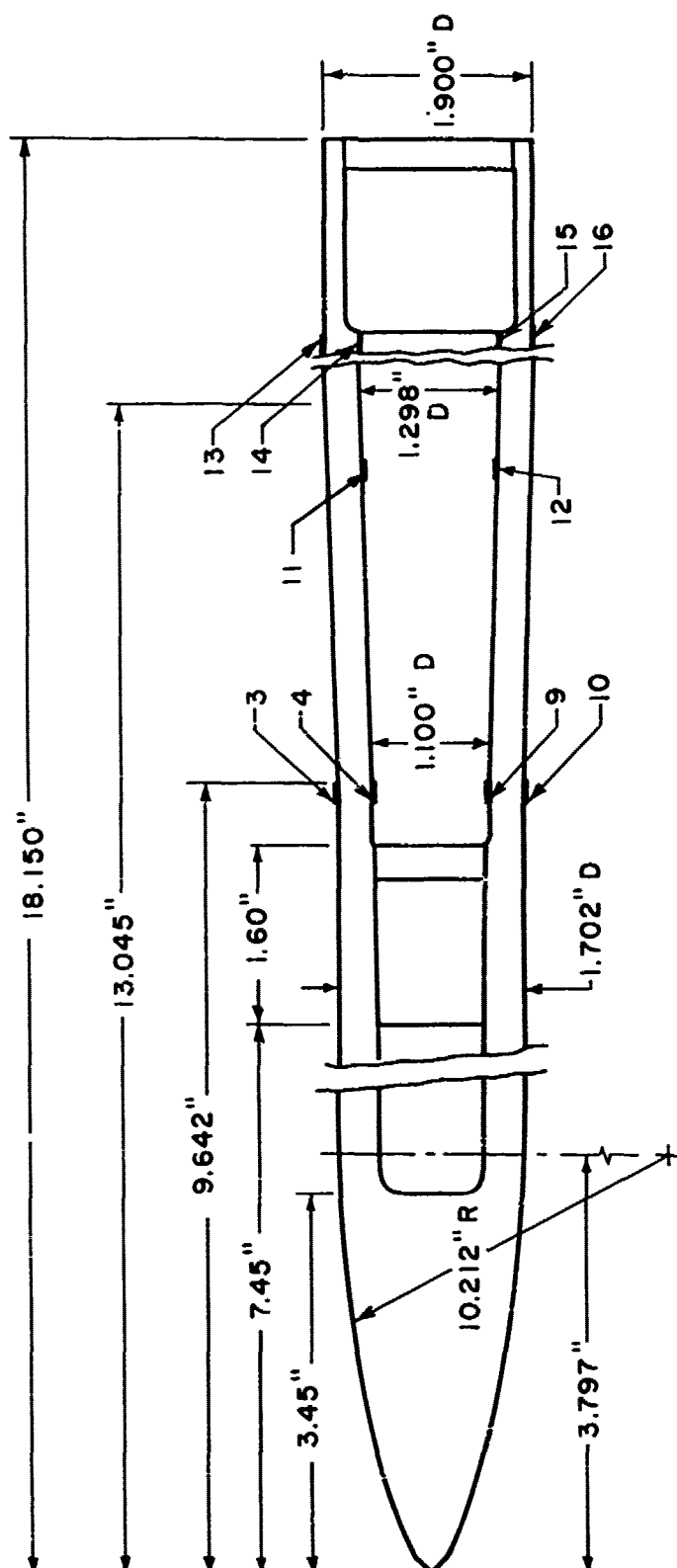
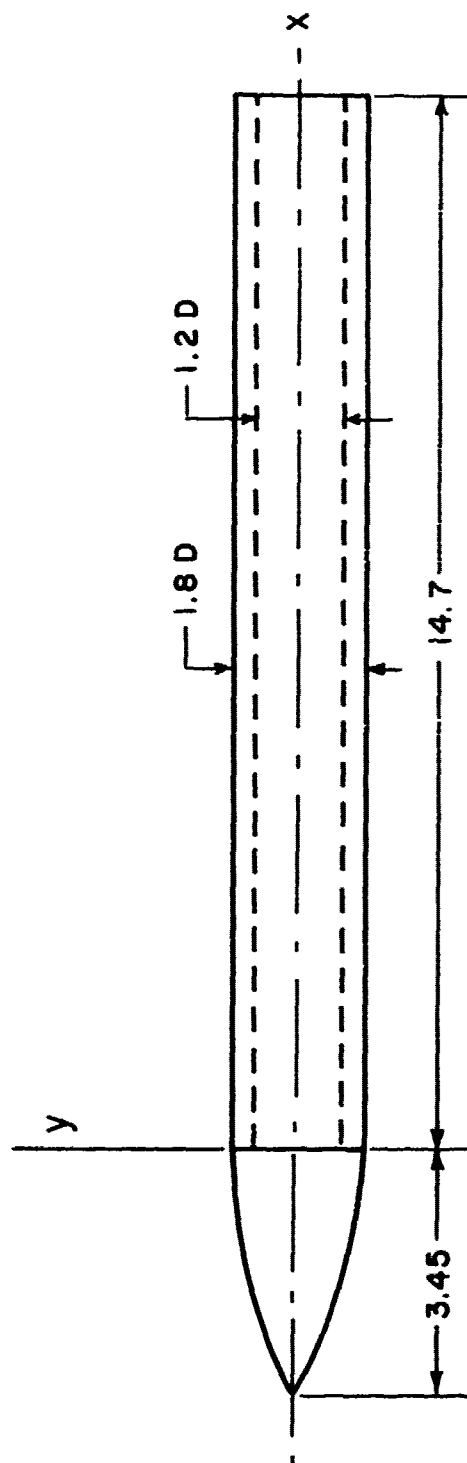
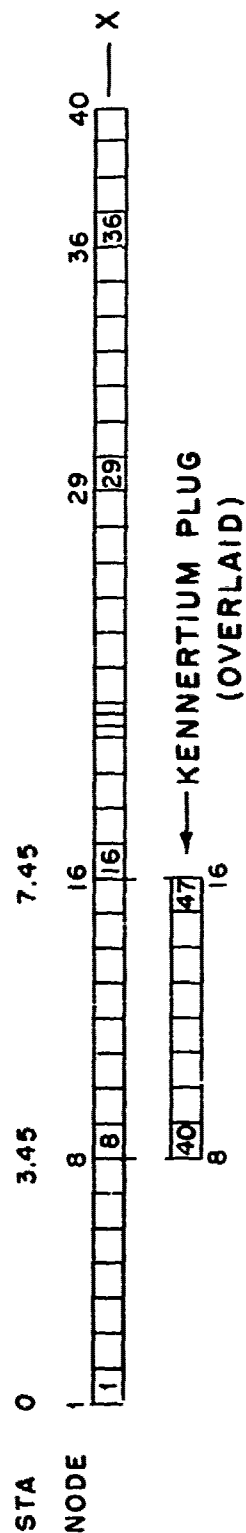


Figure 10. DNA-SANDIA vehicle employed in reverse ballistic test.



### IDENTIFICATION MODEL



### FINITE ELEMENT MODEL

Figure 11. Idealization of DNA-SANDIA vehicle for identification problem and finite element model for calculation of response from identical force.



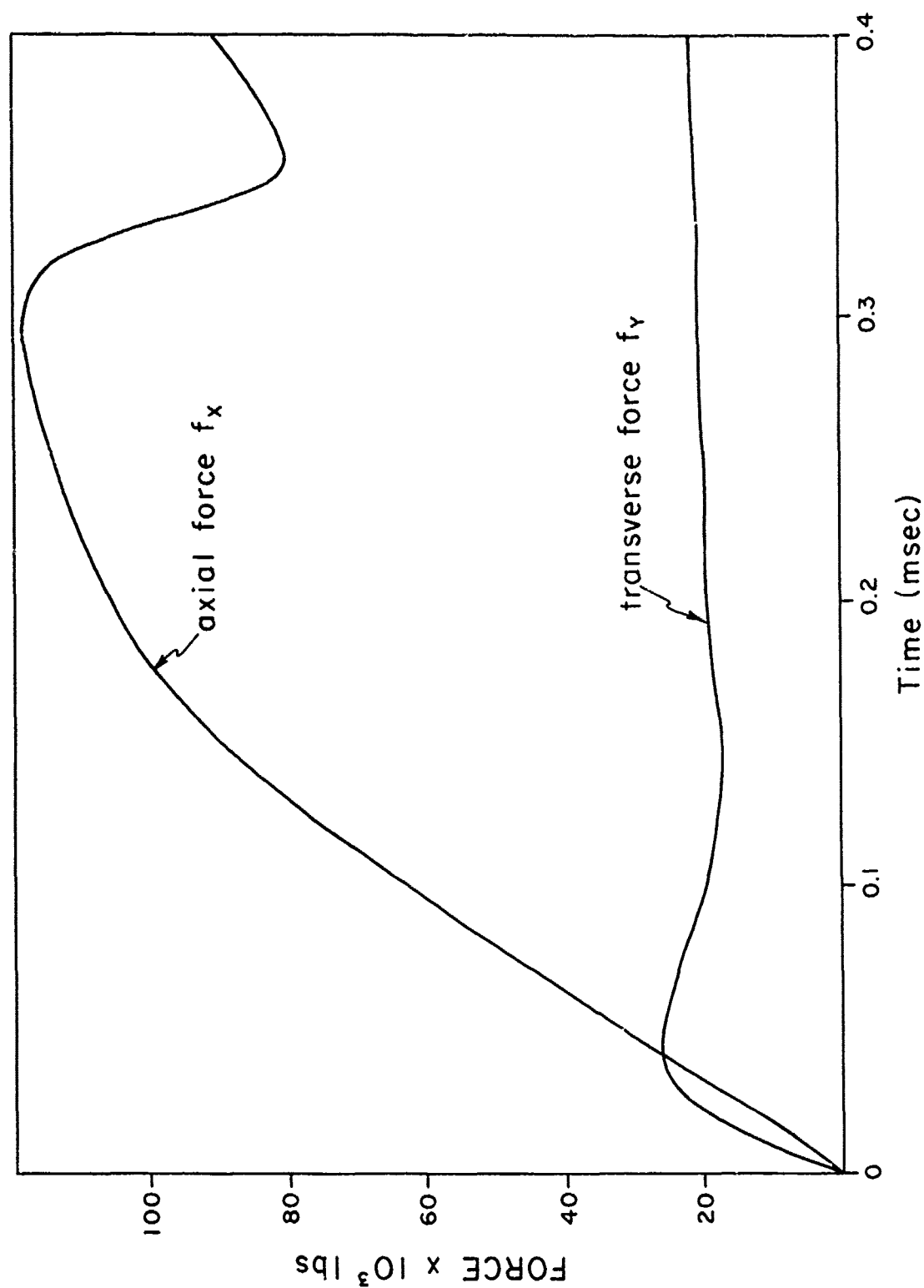


Figure 12. Forces identified on nose.

# STA 7.45 ACC-Z

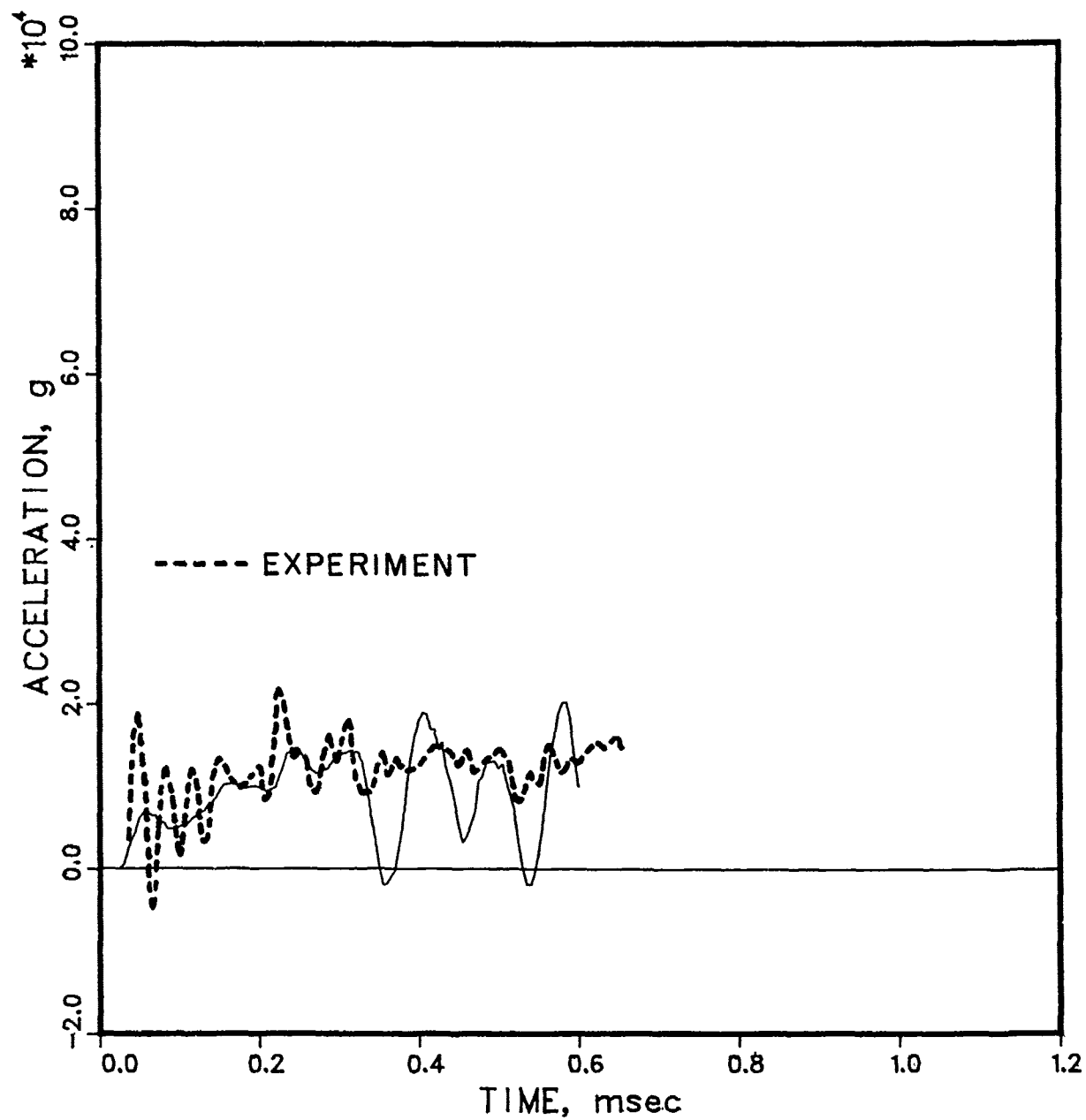


Figure 13. Axial acceleration (x-component) at station 7.45 (Accelerometer 2)

# STA 16.35 ACC-Z

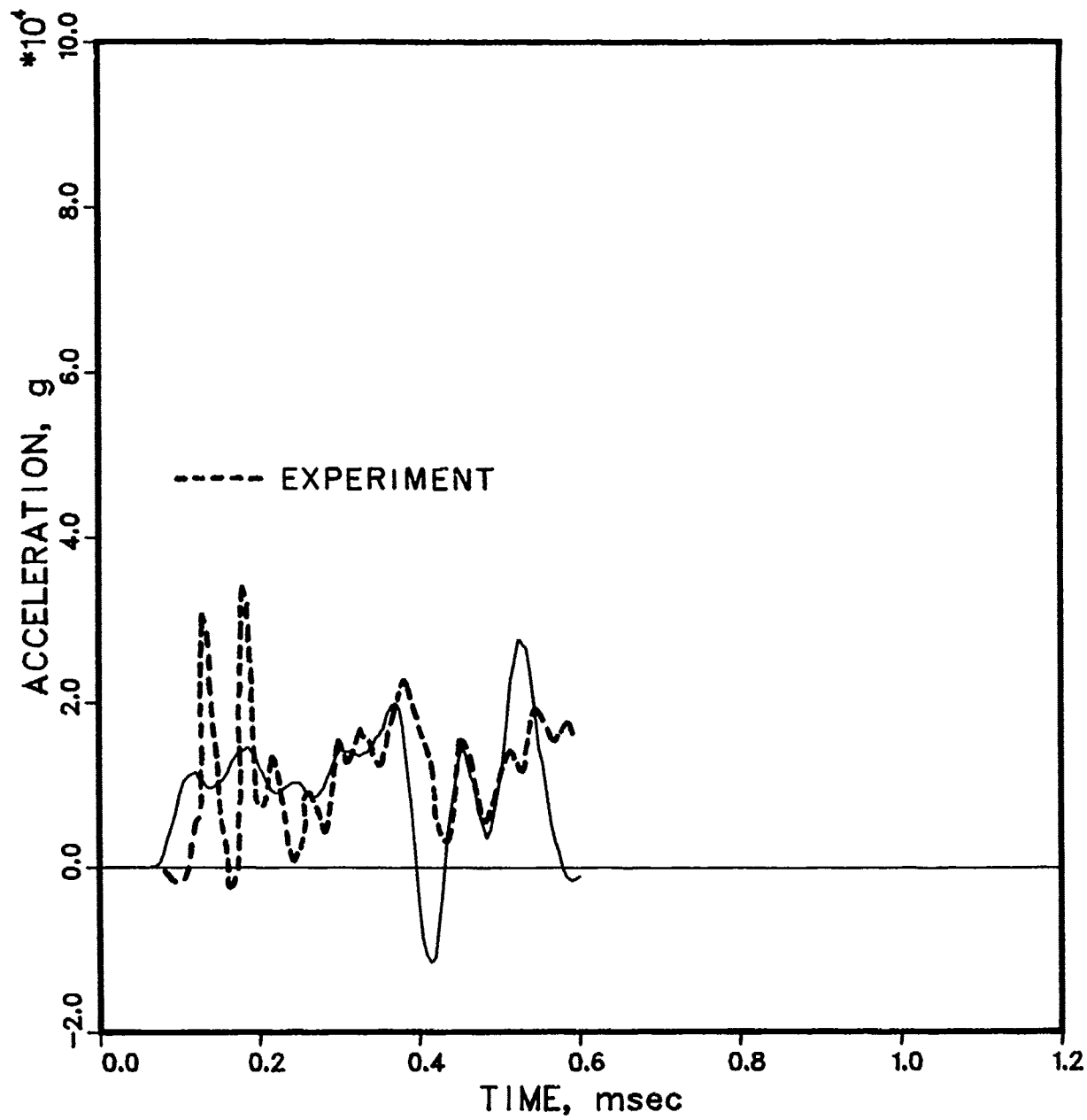


Figure 14. Axial acceleration (x-component) at station 16.35 (Accelerometer 4)

# STA 7.45 ACC-R

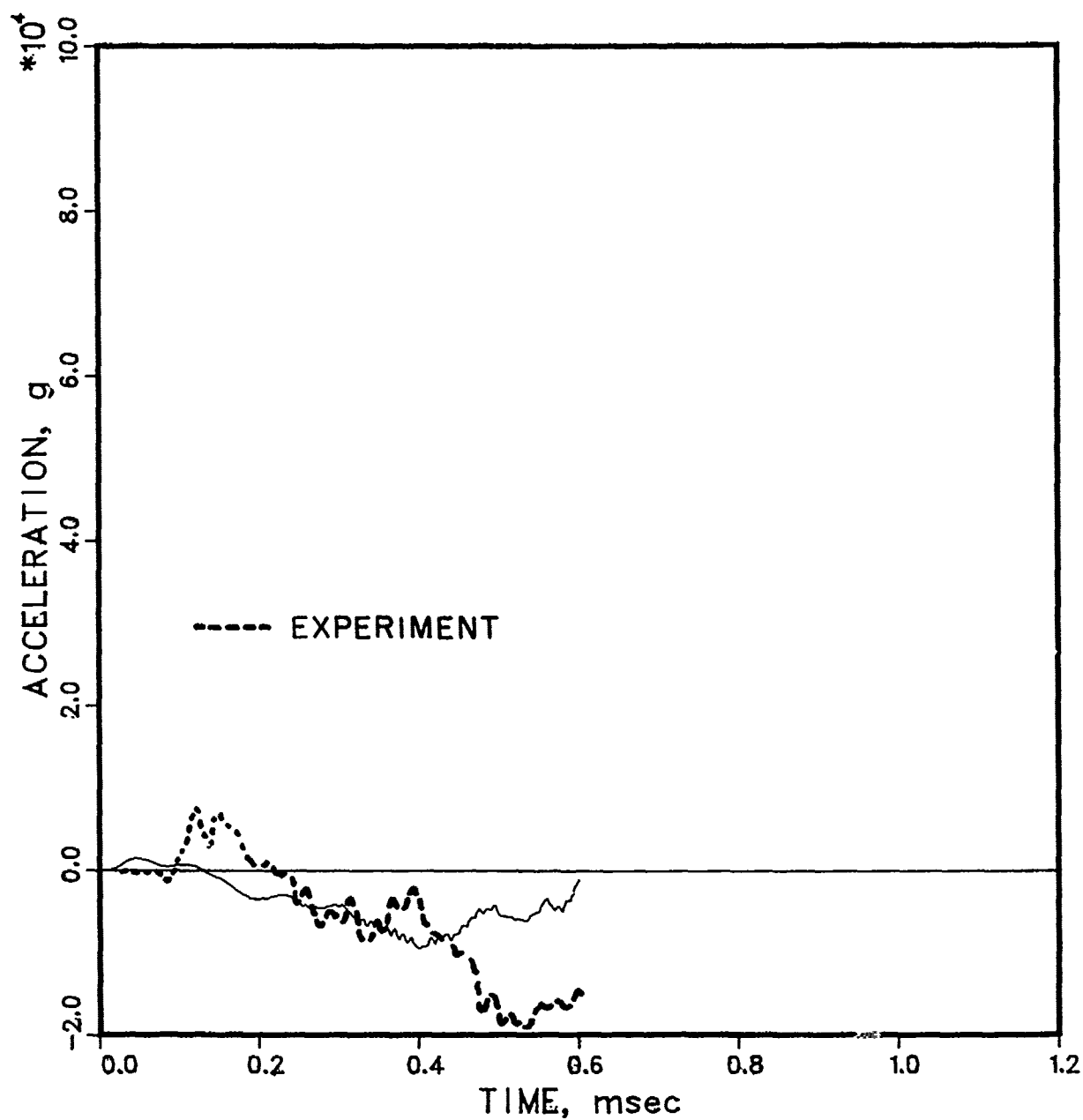


Figure 15. Lateral acceleration (y-component) at station 7.45 (Accelerometer 1)

# STA 16.35 ACC-R

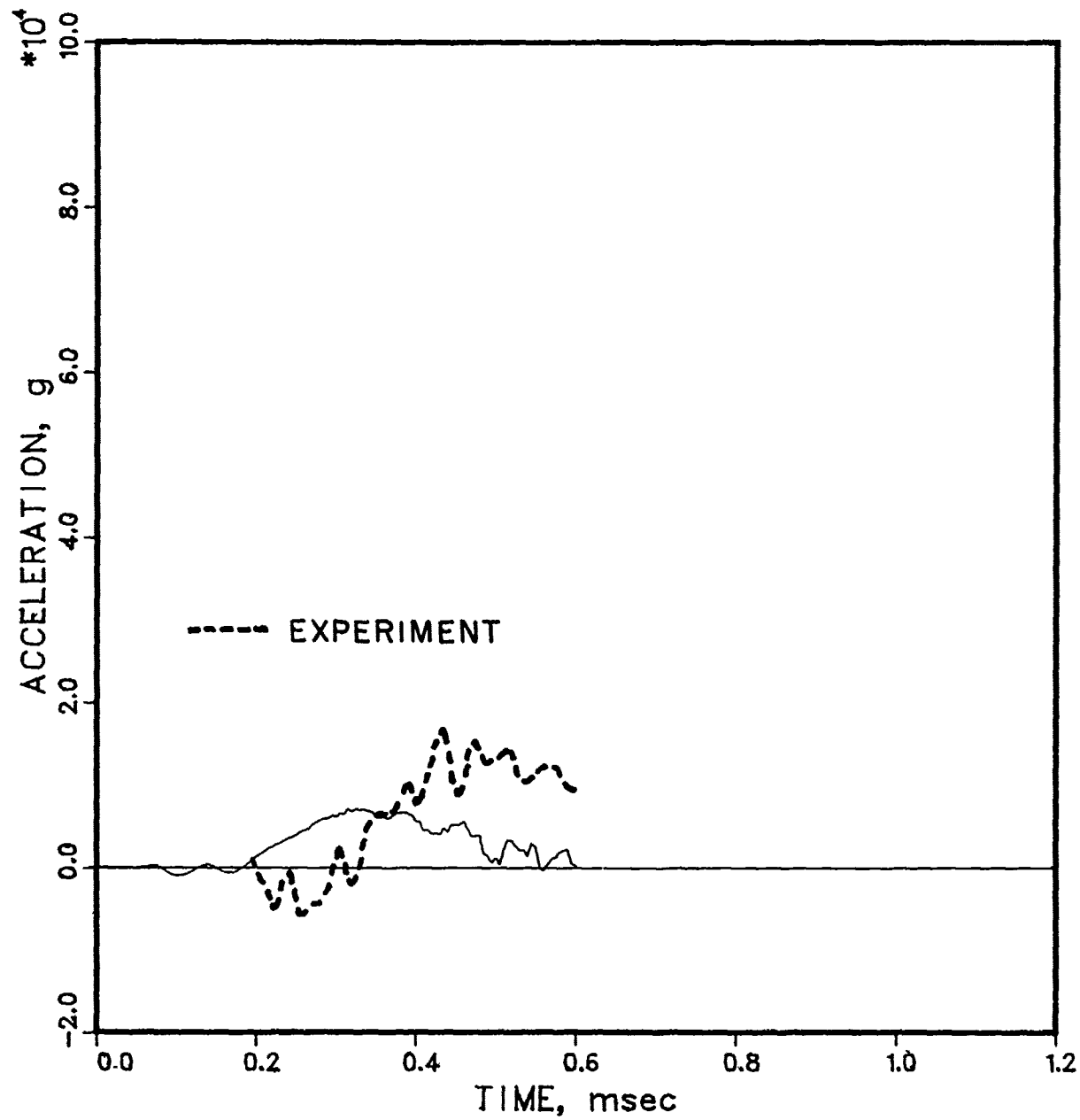


Figure 16. Lateral acceleration (y-component) at station 16.35 (Accelerometer 3)

# STA 9.6 EPS-OUT-T

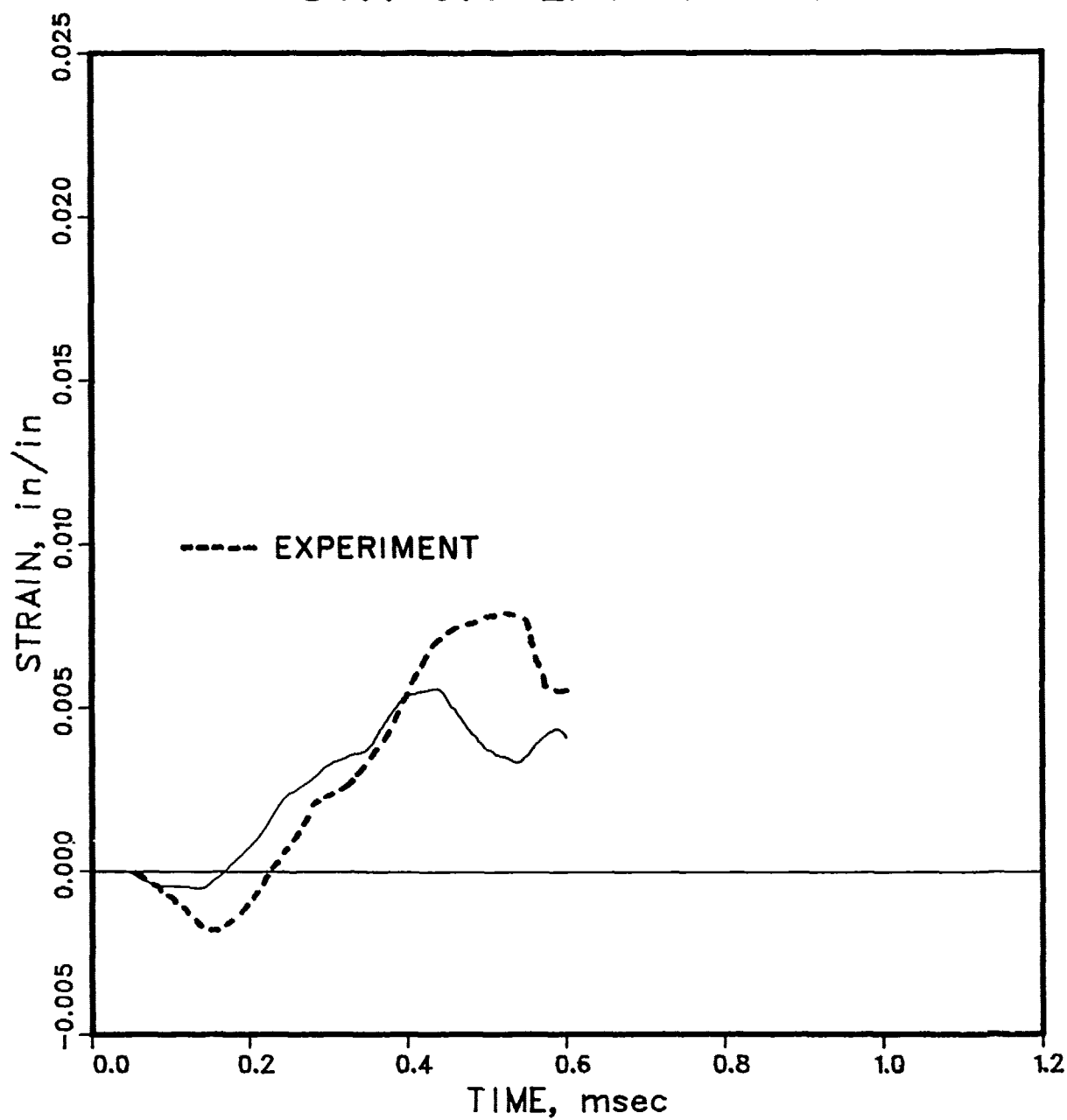


Figure 17. Strain (outside top) at station 9.6 (Strain gauge 3)

# STA 9.6 EPS-OUT-B

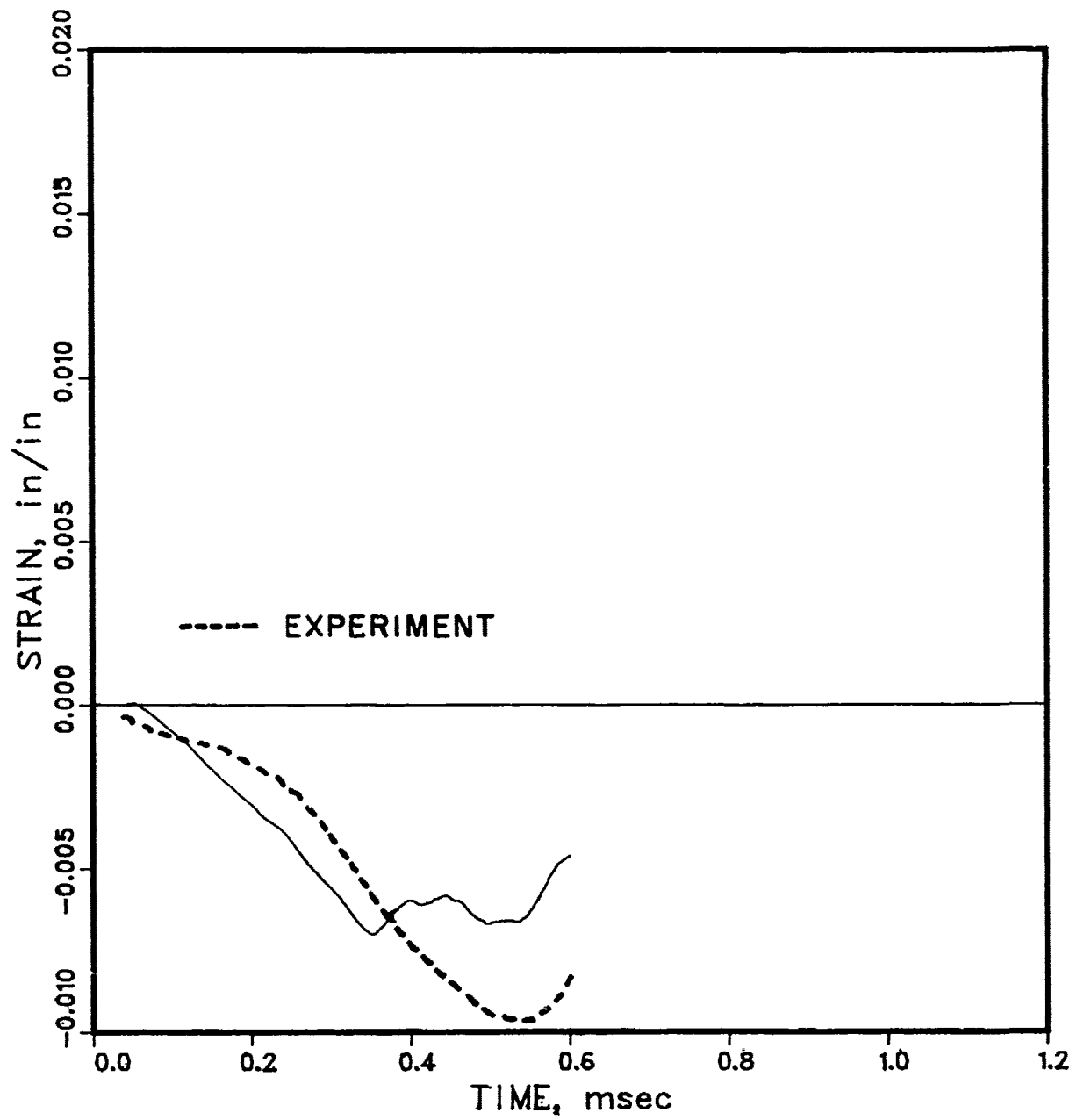


Figure 18. Strain (outside bottom) at station 9.6 (Strain gauge 10)

# STA 9.6 EPS-INS-T

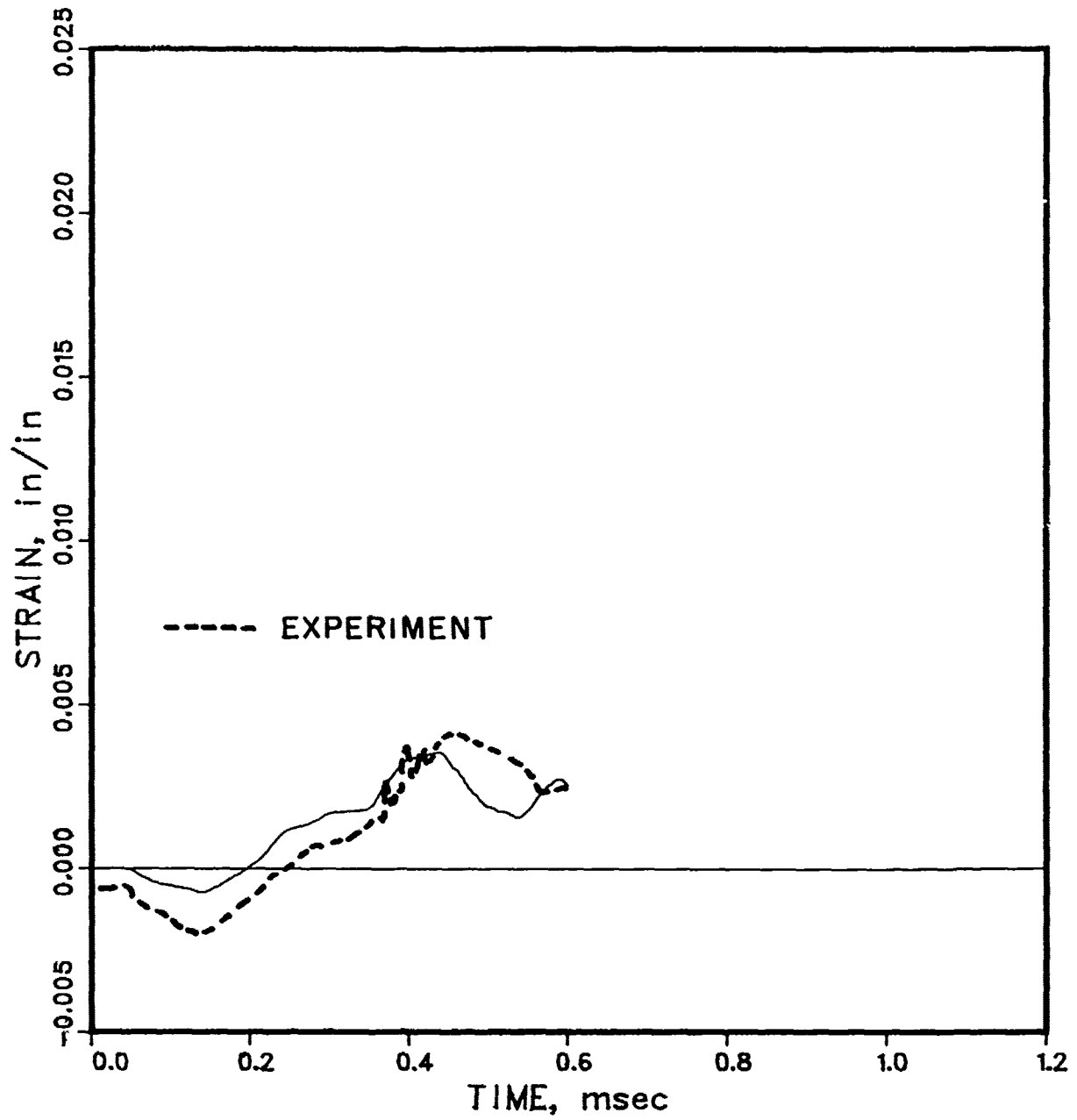


Figure 19. Strain (inside top) at station 9.6 (Strain gauge 4)



# STA 12.6 EPS-OUT-T

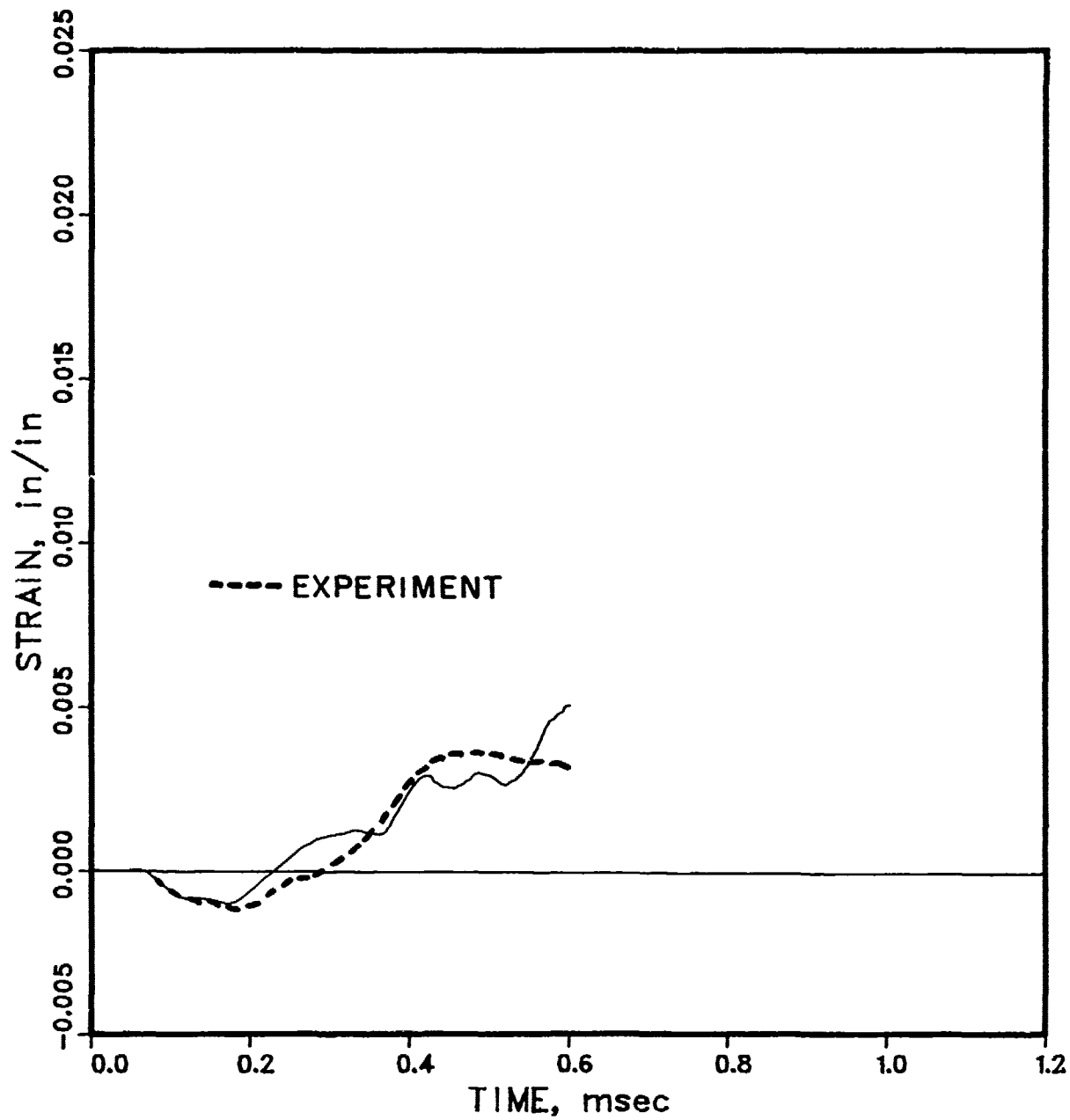


Figure 20. Strain (outside top) at station 12.6 (Strain gauge 11)

# STA 12.6 EPS-INS-B

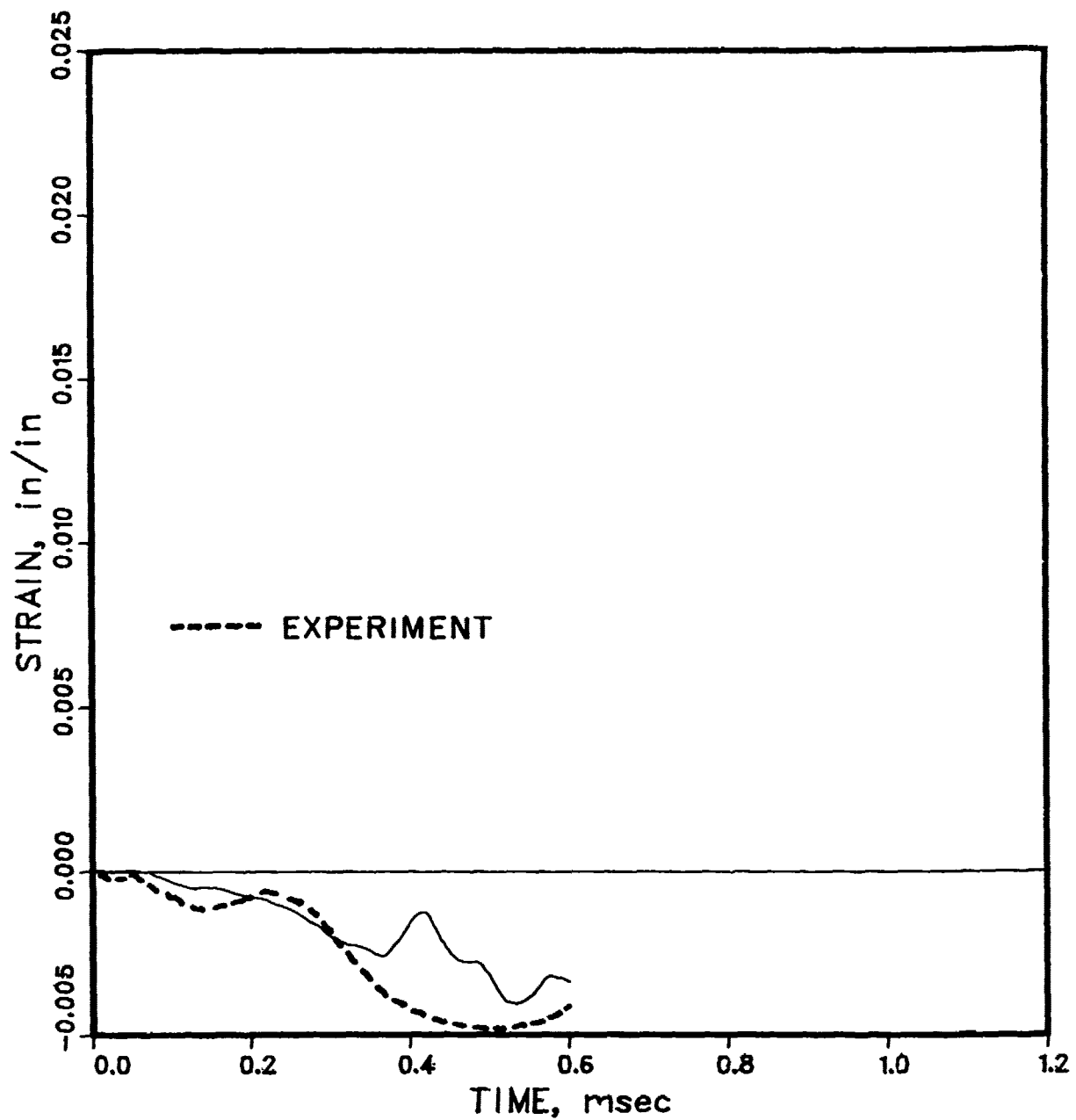


Figure 21. Strain (inside bottom) at station 12.6 (Strain gauge 12)

# STA 16.0 EPS-OUT-T

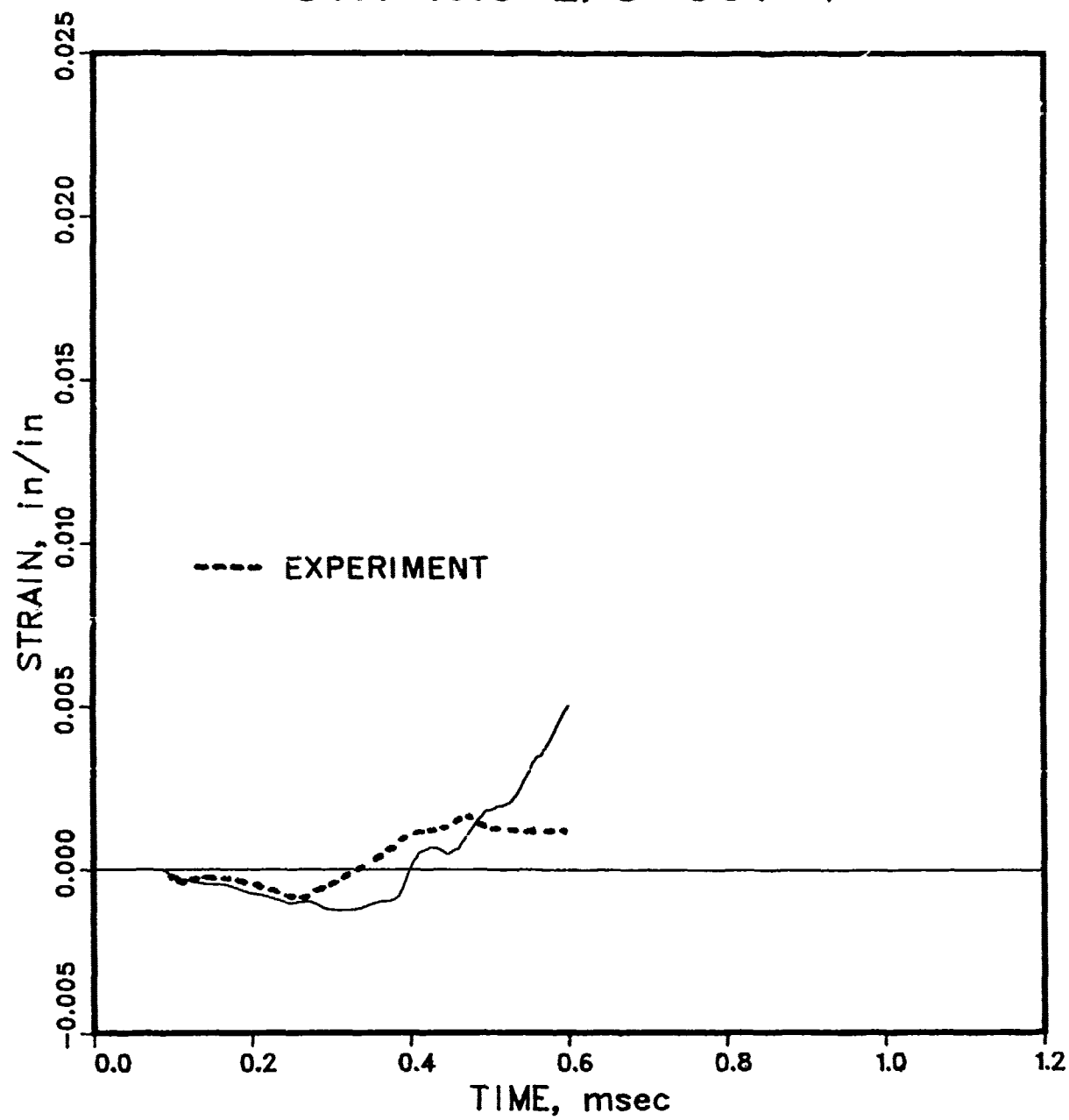


Figure 22. Strain (outside top) at station 16 (Strain gauge 13)

# STA 16.0 EPS-INS-B

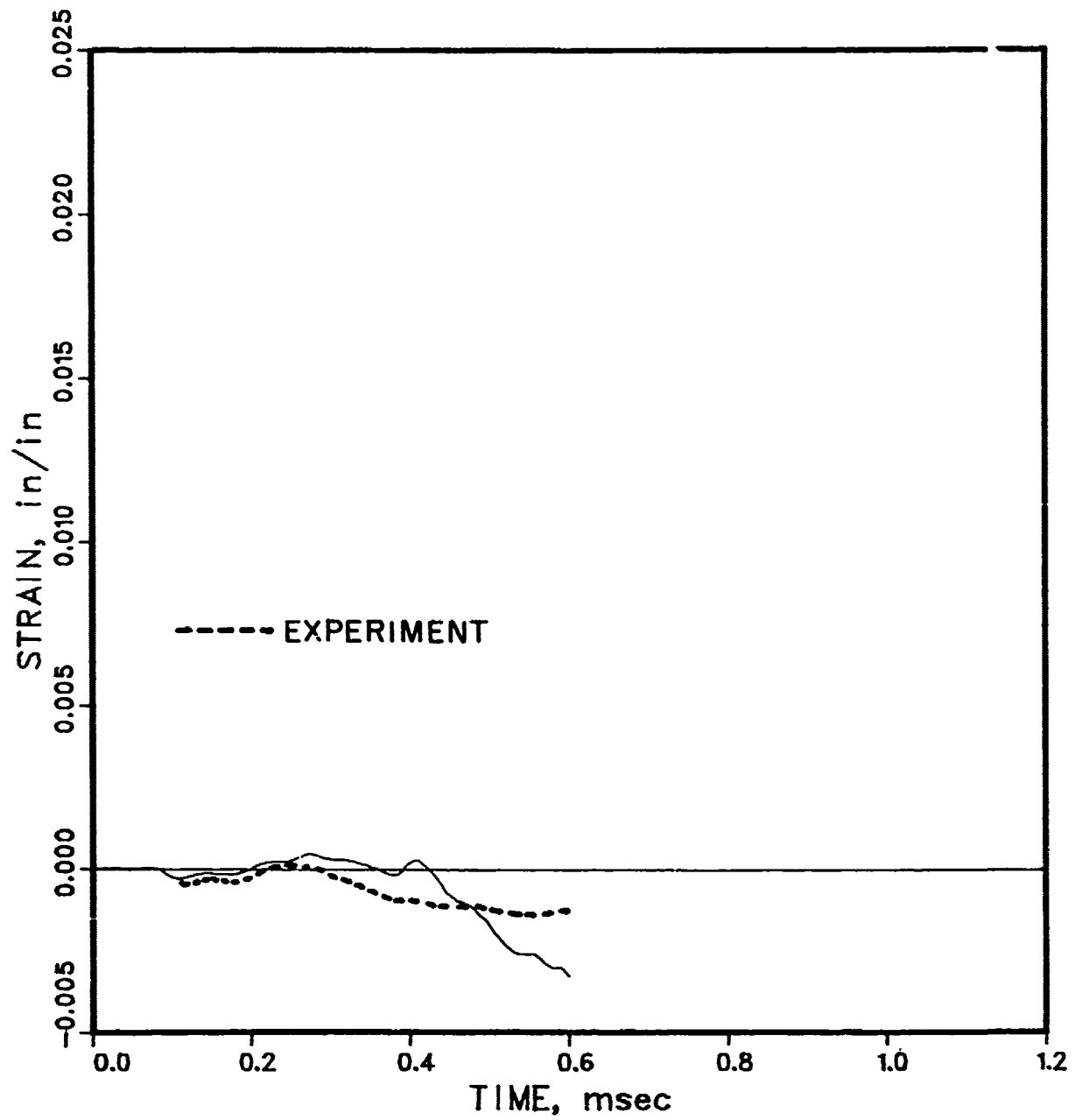


Figure 23. Strain (inside bottom) at station 16 (Strain gauge 15)

#### REFERENCES

1. Creighton, D.C. "Correlation of Additional Reverse Ballistic Test Data", U.S. Army Waterways Experiment Station Report on Work Unit 18, Subtask SB211, for DNA, August 1978.
2. Wagner, M.H., Fulton, C.C. and Goerke, S.W., "Calculation of Reverse Ballistic Test into Dakota Sandstone at 1800 Ft./sec.", California Research and Technology, Contract DNA001-76-C-0157, February 1976.
3. Belytschko, T.B., "Semianalytic Methods for Axial Response Analysis of Penetrators," DNA Report, DNA 4044F, June 1976.
4. Belytschko, T.B. and Mullen, R.M. "WHAMS, A Program for the Transient Analysis of Structures and Continua", Structural Mechanics Software Series, ed. by N. Perrone and W. Pilkey, Vol. 2, University Press of Virginia, pp. 151-212, 1978.
5. Holmes, N. and Belytschko, T.B., "Postprocessing of Finite Element Transient Response Calculations by Digital Filters", Computers and Structures, Vol. 6, 211-216, 1976.

## DISTRIBUTION LIST

### DEPARTMENT OF DEFENSE

Assistant to the Secretary of Defense  
Atomic Energy  
ATTN: Executive Assistant

Defense Advanced Rsch Proj Agency  
ATTN: TIO

Defense Intelligence Agency  
ATTN: DB-4M  
ATTN: DB-4C, E. O'Farrell  
ATTN: DT-2  
ATTN: RDS-3A

Defense Nuclear Agency  
ATTN: SPAS  
4 cy ATTN: TITL  
5 cy ATTN: SPSS

Defense Technical Information Center  
12 cy ATTN: DD

Field Command  
Defense Nuclear Agency  
ATTN: FCPR

Field Command  
Defense Nuclear Agency  
Livermore Branch  
ATTN: FCPRL

Interservice Nuclear Weapons School  
ATTN: TIV

Joint Strat Tgt Planning Staff  
ATTN: JLA  
ATTN: NRI-STINFO Library

NATO School (SHAPE)  
ATTN: U.S. Documents Officer

Undersecretary of Def for Rsch & Engrg  
ATTN: Strategic & Space Systems (OS)

### DEPARTMENT OF THE ARMY

Chief of Engineers  
Department of the Army  
2 cy ATTN: DAEN-MCE-D  
2 cy ATTN: DAEN-RDL

Deputy Chief of Staff for Ops & Plans  
Department of the Army  
ATTN: DAMO-NC

Deputy Chief of Staff for Rsch Dev & Acq  
Department of the Army  
ATTN: DAMA-CSS-H, N. Barron

Engineer Studies Center  
Department of the Army  
ATTN: DAEN-FES

Gator Mine Program  
Department of the Army  
ATTN: E. Lindsey

### DEPARTMENT OF THE ARMY (Continued)

Harry Diamond Laboratories  
Department of the Army  
ATTN: DELHD-N-P  
ATTN: DELHD-N-P, J. Gwaltney

U.S. Army Armament Material Readiness Cmd  
ATTN: MA Library

U.S. Army Ballistic Research Labs  
ATTN: DRDAR-BLT  
ATTN: DRDAR-BLT, G. Grabarek  
ATTN: DRDAR-BLT, J. Keefer  
ATTN: DRDAR-BLT, A. Ricchiazzi  
ATTN: DRDAR-BLT  
ATTN: DRDAR-BLT, G. Roecker  
2 cy ATTN: DRDAR-TSB-S

U.S. Army Cold Region Res Engr Lab  
ATTN: G. Swinow

U.S. Army Concepts Analysis Agency  
ATTN: CSSA-ADL

U.S. Army Engineer Center  
ATTN: ATZA

U.S. Army Engineer Div Huntsville  
ATTN: HNDED-SR

U.S. Army Engineer Div Missouri River  
ATTN: Technical Library

U.S. Army Engineer School  
ATTN: ATZA-DTE-ADM  
ATTN: ATZA-CDC

U.S. Army Engr Waterways Exper Station  
ATTN: J. Strange  
ATTN: D. Butler  
ATTN: WESSD, J. Jackson  
ATTN: B. Rohani  
ATTN: WESSE, L. Ingram  
ATTN: Library  
ATTN: WESSA, W. Flathau

U.S. Army Mat Cmd Proj Mngr for Nuc Munitions  
ATTN: DRCPM-NUC

U.S. Army Material & Mechanics Rsch Ctr  
ATTN: Technical Library

U.S. Army Materiel Dev & Readiness Cmd  
ATTN: DRXAM-TL

U.S. Army Materiel Sys Analysis Activity  
ATTN: DRXSY-D, J. Sperrazza

U.S. Army Missile R&D Command  
ATTN: RSIC  
ATTN: F. Fleming  
ATTN: DRCPM-PE, W. Jann

U.S. Army Mobility Equip R&D Cmd  
ATTN: DRDME-WC  
ATTN: DRDME-XS

DEPARTMENT OF THE ARMY (Continued)

U.S. Army Nuclear & Chemical Agency  
ATTN: Library

U.S. Army War College  
ATTN: Library

DEPARTMENT OF THE NAVY

Marine Corps  
Department of the Navy  
ATTN: POM

Marine Corp Dev & Education Command  
Fire Support Section  
Department of the Navy  
ATTN: D091, J. Hartnedy

Naval Construction Battalion Center  
ATTN: Code L08A  
ATTN: Code L51, R. Odello

Naval Explosive Ord Disposal Fac  
ATTN: Code 504, J. Petrousky

Naval Postgraduate School  
ATTN: Code 1424 Library

Naval Research Laboratory  
ATTN: Code 2627

Naval Sea Systems Command  
ATTN: SEA-9931G  
ATTN: SEA-033

Naval Surface Weapons Center  
White Oak Laboratory  
ATTN: Code U401, M. Kleinerman  
ATTN: Code F31  
ATTN: Code X211

Naval Surface Weapons Center  
ATTN: Tech Library & Info Svcs Branch

Naval Weapons Center  
ATTN: Code 266, C. Austin  
ATTN: Code 233

Naval Weapons Evaluation Facility  
ATTN: Code 10

Office of the Chief of Naval Operations  
ATTN: OP 982  
ATTN: OP 654C3, R. Piacesi  
ATTN: OP 982E, M. Lenzini

Strategic Systems Project Office  
Department of the Navy  
ATTN: NSP-43

DEPARTMENT OF THE AIR FORCE

Air Force Armament Laboratory  
ATTN: ADTC/XRS, M. Valentine  
3 cy ATTN: DLRV, J. Collins

Air Force Institute of Technology  
ATTN: Library

DEPARTMENT OF THE AIR FORCE (Continued)

Air Force Weapons Laboratory  
Air Force Systems Command  
ATTN: SUL

Assistant Chief of Staff  
Intelligence  
Department of the Air Force  
ATTN: INT

Strategic Air Command/INT  
Department of the Air Force  
ATTN: J. McKinney

Deputy Chief of Staff  
Research, Development, & Acq  
Department of the Air Force  
ATTN: R. Steere

Foreign Technology Division  
Air Force Systems Command  
ATTN: NIIS Library

Headquarters Space Division  
Air Force Systems Command  
ATTN: RSS

Oklahoma State University  
Fld Off for Wpns Effectiveness  
Department of the Air Force  
ATTN: E. Jackett

Rome Air Development Center  
Air Force Systems Command  
ATTN: TSLD

DEPARTMENT OF ENERGY

Department of Energy  
Albuquerque Operations Office  
ATTN: CTID

Department of Energy  
ATTN: OMA/RD&T

Department of Energy  
Nevada Operations Office  
ATTN: Mail & Records for Tech Lib

DEPARTMENT OF ENERGY CONTRACTORS

Lawrence Livermore National Lab  
ATTN: Technical Info Dept Library  
ATTN: L-504, M. Wilkins  
ATTN: J. Goudreau

Los Alamos National Scientific Lab  
ATTN: M/S632, T. Dowler  
ATTN: MS 364

Sandia National Laboratories  
Livermore National Laboratory  
ATTN: Library & Security Class Div

DEPARTMENT OF ENERGY CONTRACTORS (Continued)

Sandia National Lab  
ATTN: 3141  
ATTN: W. Caudle  
ATTN: A. Chabai  
ATTN: J. Colp  
ATTN: W. Herrman  
ATTN: W. Altsmeirer  
ATTN: W. Patterson  
ATTN: J. Kaizur

OTHER GOVERNMENT AGENCIES

Central Intelligence Agency  
ATTN: OSWR/NED  
  
Federal Emergency Management Agency  
ATTN: Hazard Eval & Vul Red Div  
  
NASA  
AMES Research Center  
ATTN: R. Jackson  
  
U.S. Nuclear Regulatory Commission  
ATTN: R. Whipp for Div of Sec for L. Shao

DEPARTMENT OF DEFENSE CONTRACTORS

Aerospace Corp  
ATTN: Technical Information Services  
  
Agbabian Associates  
ATTN: M. Agbabian  
  
Applied Theory, Inc  
2 cy ATTN: J. Trulio  
  
Avco Research & Systems Group  
ATTN: D. Henderson  
ATTN: P. Grady  
ATTN: Library A830  
  
BDM Corp  
ATTN: Corporate Library  
ATTN: T. Neighbors  
  
Boeing Co  
ATTN: Aerospace Library  
  
California Research & Technology, Inc  
ATTN: K. Kreyenhagen  
ATTN: Library  
  
California Research & Technology, Inc  
ATTN: D. Orphal  
  
EG&G Washington Analytical Services Center, Inc  
ATTN: Library  
  
Engineering Societies Library  
ATTN: A. Mott  
  
General Dynamics Corp  
ATTN: R. Dibrell  
  
General Electric Company—TEMPO  
ATTN: DASIAC  
  
Honeywell, Inc  
ATTN: T. Helvig

DEPARTMENT OF DEFENSE CONTRACTORS (Continued)

Institute for Defense Analyses  
ATTN: Classified Library  
  
Kaman Avidyne  
ATTN: E. Criscione  
ATTN: N. Hobbs  
ATTN: Library  
  
Kaman Sciences Corp  
ATTN: Library  
  
Lockheed Missiles & Space Co, Inc  
ATTN: Technical Information Center  
  
Lockheed Missiles & Space Co, Inc  
ATTN: M. Culp  
ATTN: TIC-Library  
  
Martin Marietta Corp  
ATTN: H. McQuaig  
ATTN: A. Cowan  
ATTN: M. Anthony  
  
Merritt CASES, Inc  
ATTN: Library  
ATTN: J. Merritt  
  
Nathan M. Newmark Consult Eng Svcs  
ATTN: W. Hall  
ATTN: N. Newmark  
  
University of New Mexico  
Dept of Police & Parking Security  
ATTN: G. Triandafalidis  
  
Pacific-Sierra Research Corp  
ATTN: H. Brode  
  
Pacifica Technology  
ATTN: G. Kent  
ATTN: R. Bjork  
  
Physics International Co  
ATTN: Technical Library  
ATTN: L. Behrmann  
  
R & D Associates  
ATTN: A. Field  
ATTN: Technical Information Center  
ATTN: P. Rausch  
ATTN: W. Wright, Jr  
ATTN: J. Lewis  
ATTN: P. Haas  
  
Rand Corp  
ATTN: Library  
  
Science Applications, Inc  
ATTN: Technical Library  
  
Science Applications, Inc  
ATTN: W. Layson  
  
SRI International  
ATTN: J. Colton  
ATTN: G. Abrahamson



DEPARTMENT OF DEFENSE CONTRACTORS (Continued)

Systems, Science & Software, Inc

ATTN: R. Sedgewick

ATTN: Library

Terra Tek, Inc

ATTN: Library

TRW Defense & Space Sys Group

ATTN: Technical Information Center

ATTN: N. Lipner

DEPARTMENT OF DEFENSE CONTRACTORS (Continued)

TRW Defense & Space Sys Group

ATTN: E. Wong

ATTN: P. Dai

Weidlinger Assoc, Consulting Engineers

ATTN: J. McCormick

ATTN: M. Baron

Weidlinger Assoc, Consulting Engineers

ATTN: J. Isenberg